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Geotechnical and Structures Laboratory

US Army Corps of Engineers®
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Full-Scale Instrumented Testing and Analysis of Matting Systems for Airfield Parking Ramps and Taxiways

Chad A. Gartrell

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Final report

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Abstract: The U.S. military requires the ability to rapidly deploy troops, equipment, and materials anywhere in the world. Recent operations have brought attention to the need to utilize austere, unsurfaced, and sometimes sub-standard airfields within a theater of interest. These airfields may require additional taxiways and aprons. One option for the rapid construction of such is airfield matting systems. The focus of the work for this thesis was commercially available airfield matting systems to support large military transport aircraft, such as the C-17. Several test sections with differing strength soils were built with chosen mats tested in an elimination method, using a load cart that simulates contingency loading of one main gear of the C-17. Matting systems were evaluated based on logistical and assembly requirements, and deformation and damage sustained during traffic. A modeling effort was performed to investigate the potential of a simple model to predict the response of these matting systems under full-scale testing.

Preface

The research described herein was conducted as part of the Joint Rapid Airfield Construction (JRAC) program. Conducted during fiscal years 2002–2007, JRAC was a comprehensive demonstration-based research and development program executed by the U.S. Army Engineer Research and Development Center (ERDC). The JRAC program was sponsored by Headquarters, U.S. Army Corps of Engineers.

This report was submitted by Chad A. Gartrell of the ERDC Geotechnical and Structures Laboratory (GSL) in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering in the Department of Civil and Environmental Engineering, Mississippi State University (MSU). Thesis committee members were Drs. Thomas D. White and Isaac L. Howard, MSU, and Dr. Gary L. Anderton, Airfields and Pavements Branch (APB), GSL. Additional helpful support and technical guidance were provided by Dr. Reed B. Freeman, Dr. Donald M. Smith, Dr. J. Kent Newman, Louis W. Mason, and Quint Mason of APB; Harold T. Carr of the ERDC Information Technology Laboratory; and Dennis Beausoliel and Charles J. Wilson of the ERDC Directorate of Public Works.

The work was conducted under the supervision of Dr. Anderton, Acting Chief, APB; Dr. Larry N. Lynch, Chief, Engineering Systems and Materials Division; Dr. William P. Grogan, Deputy Director, GSL; and Dr. David W. Pittman, Director, GSL.

COL Richard B. Jenkins was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

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CHAPTER I

INTRODUCTION

Background

Development of airfield capabilities in a minimum timeframe is part of a comprehensive program being conducted at the U.S. Army Engineer Research and Development Center (ERDC) called “Joint Rapid Airfield Construction,” or JRAC. Objectives of the program are to (a) optimize contingency airfield selection from those available in a theater of interest, (b) reduce airfield construction timelines, and (c) utilize advances in rapid soil stabilization. The JRAC program will provide military engineers with new tools, methods, and technologies to construct and/or upgrade contingency airfields. In addition, the JRAC program will reduce the logistical requirements to build or repair contingency airfields. This will be accomplished by minimizing material and equipment needed for construction.

The JRAC program is a six-year research effort that began in 2002 and includes over 30 individual work units focused on providing engineering solutions to increase the U.S. military’s capability to rapidly build or upgrade contingency airfields. The program includes two large “live exercise” technology demonstrations in which combat engineers use equipment, methods, and materials developed in the program. The first demonstration took place in 2004 at Fort Bragg, North Carolina, and the second event was conducted in 2007 in Australia’s Northern Territory.

This thesis describes work performed under the Rapid Maximum-On-Ground (MOG) Enhancement work unit of the JRAC program. Maximum-On-Ground refers to the maximum number of aircraft that can occupy an airfield at one time without interfering with each aircraft's access to the active runway. For the fighting force, more planes on the ground, translates into a faster resource deployment and force projection. Matting systems (typically, but not always, flat plate units manufactured from an array of materials and connected by overlapping edges and/or pins or mechanical interlocks) have proven to be an effective means of rapidly constructing taxiways and parking aprons and thereby increasing an airfield's MOG.

Problem Statement

In most rapid military deployment scenarios, candidate airfields are usually austere. In many cases, these are dirt or grass strips used by private, light commercial or agricultural aircraft. Such sites often consist of a single runway with no taxiways or parking aprons. This scenario restricts airfield operations to only one aircraft on the ground at any given time, or a MOG of one. By adding just one short loop taxiway and an apron sized for parking one aircraft, the MOG capability rises from one to three aircraft. The taxiway area, the apron, and the airstrip provide one parking area each.

There are several options, using current technologies, to remedy the problem of insufficient taxiway and apron space. The obvious choice is new construction. In most instances, new construction of a permanent facility is based on a minimum life cycle of 20 years. The timeline to provide a "permanent facility" will not meet the rapid deployment needs of the future force. In addition, logistical requirements of this option

would be prohibitive. Material availability and quality for this option may be questionable at best. A second option is soil stabilization. Soil stabilization can be effective, and when designed correctly, offers a solution adequate for the required number of aircraft passes to complete a mission (little as one week up to several months). However, stabilization does require specialized equipment that may need to be transported to the site via aircraft. In addition, this method will usually involve the use of products like portland cement and polymers that require curing prior to traffic application. A third option, offering similar traffic pass levels and simpler construction procedures, is airfield matting.

The matting option requires limited construction equipment for the initial grading and surface preparation prior to mat installation. Often the equipment needed will be available in a contingency airfield environment. Unlike soil stabilization, airfield matting can support traffic immediately after installation. In addition, airfield matting systems can be reused. Stabilization is a one-time-only application. Properly designed matting systems also offer easier surface maintenance in that damaged mats can be removed and replaced.

Airfield matting has been around since World War II with one of the more well-known original matting systems being the Pierced Steel Planking or Marston Matting. Although its primary purpose has remained essentially the same, mat materials, geometry, design, and assembly have changed. Today a number of commercial matting systems are available. Typical mat material includes steel, aluminum, fiberglass, polymers, and composites and combinations of the same. Earliest airfield mat were required to support relatively light B-17 bombers or the P-51 Mustang fighter aircraft.

Today, mats are required to support the much heavier C-17 Globemaster transport aircraft and F-15 Eagle fighter aircraft. Assembly has changed as well. Some mats are in rolls, some are folded, and others are received as individual panels. Individual mat connections vary, and include tongue and groove, locking rails, threaded bolt and bushing, locking pins, and built-in cam pins.

Many commercial matting systems today were developed by industry. The oil and gas exploration and production industry is one area of application. Oil and gas exploration and production of oil can force men, materials, and equipment into difficult terrain, such as the swamps and bayous of Louisiana. Matting systems such as the Dura-Base® system were developed to provide a better alternative to a widely used but expensive and short-lived oak timber mat. In Canada and Alaska, with environmental concerns over destruction of the tundra regions, matting systems such as Dura-Base® and Rolla-Road® provided a protective surface that better distributes loads of vehicles and equipment, thereby protecting these natural regions.

The important issues with matting systems, especially from the perspective of MOG expansion, are strength, size and ease of use. When considering airfield matting systems, the following questions arise:

- What matting systems currently available are strong enough to support the aircraft of concern?
- What base soil strength must be present for a particular matting system to perform satisfactorily?

- Is the matting system size and weight compatible with logistical limitations?
- Is the matting system easily assembled and maintained?

The JRAC program goal, beginning in the spring of 2003, was to answer these questions. The Rapid MOG Enhancement work unit of the program included the task of finding commercial-off-the-shelf (COTS) matting systems capable of supporting the primary transport aircraft of the military over varying soil strengths. The primary aircrafts of interest were the C-130 Hercules and the C-17 Globemaster.

Objective and Scope

The objective of this study is to test commercially marketed matting systems over different soil base strengths using C-17 aircraft wheel loads. The end product is recommendations on the type of matting to use for the construction of contingency airfield taxiways and parking aprons to be trafficked by C-17 aircraft. Design charts are provided of expected pass levels versus expected deformation (permanent rutting) during C-17 aircraft traffic. Guidance on preliminary mat evaluation using simple models and mechanical test results of mats are provided. Further research is recommended.

During the first phase of the Rapid MOG Enhancement work unit, several different matting systems were acquired and tested with C-130 aircraft wheel loads. The lesser weight of the C-130 was used as an elimination mechanism for matting systems to be tested under the more severe C-17 wheel loads. This thesis will describe the latest testing with C-17 wheel loads. Details are presented on test section construction, traffic

and data collection, failure criteria and final results of the project. In addition, several simple models are evaluated for predicting matting system response.

It is assumed that in any JRAC scenario where an austere airfield is to be utilized, landing strip strength would be verified prior to any work being performed to increase the facility MOG. This document does not discuss procedures of the process for identifying and quantifying the austere airfield of interest prior to deployment. In addition, matting systems investigated during the Rapid MOG Enhancement work unit are not to be used on the runway. They are only valid for use in slow-rolling (taxi) and parking apron (static) applications and have not been tested for runway takeoff and landing operations of aircraft.

This document details the test section construction, traffic and data collection, failure criteria, and final results of the project. In addition, several simple models are evaluated for predicting the initial response of the matting systems.

CHAPTER II

LITERATURE REVIEW

Introduction

The concept of pavement matting and its uses is not new. Matting, in its various forms, has been around for many years. In its simplest form, matting is designed to bridge a weakened area of ground. The idea of airfield matting became of interest during World War II when military commanders saw the need to either repair existing airfields or expeditiously build new ones close to the frontlines. Since that time, matting has found multiple uses in the military, providing foreign object damage (FOD) covers for expedient repairs, creating airfield operating surfaces over base soils, spanning bomb damaged areas of runways and taxiways, providing hardened paths for beach crossings, and providing a dry tent floor during inclement weather.

With the future force concept, rapid deployment to a theater will once again demonstrate the value of matting systems. Rapid deployment involves use of austere, un-surfaced airfields to gain access to a theater quickly, quietly, and safely. On airfields, matting offers the option to rapidly construct taxiway and parking apron surfaces to increase the throughput of personnel and equipment.

This literature review examines the history of full-scale test sections for the testing and evaluation of airfield matting, much of which was conducted at the U.S. Army Engineer Research and Development Center (ERDC), located at the

Waterways Experiment Station (WES) in Vicksburg, Mississippi. In addition, modeling efforts to simplify the evaluation of existing and prototype matting systems for military applications are discussed.

Full-Scale Test Sections

There is a long history of matting design and testing, especially from the military airfield perspective. The ERDC and other military research groups have conducted numerous research projects on matting systems, beginning during and after World War II and continuing through the Vietnam War. Recently, matting work has been conducted under the Joint Rapid Airfield Program (JRAC) at the ERDC (Anderton and Gartrell, 2005). Additionally, the Rapid Parking Ramp Expansion (RPRE) Program, funded by the U.S. Air Force, was also underway at the ERDC. This effort was tasked to find a lighter and stronger replacement for the AM2 matting system, in existence since its introduction into the U.S. Air Force inventory in 1965 during the "Cold War" period (Dover et al., 2002).

During World War II, military leaders saw the importance of airfields to support operations in all theaters of action. Many times, this required the use of captured airfields close to the conflict or building new ones as quickly as possible. To provide this capability, engineers began experimenting with different types of matting materials. The traditional oak timber or "2 × 4" landing mat planks were costly and labor intensive to produce. In addition, their bulky weight made transportation to the point of need prohibitive. Military engineers began looking at lighter, more easily transported materials. Pierced Steel Planking (PSP) (Photo 1), also known as Marston Matting, was

one of the first matting systems to be widely tested. It was first demonstrated at Langley Field, Virginia in 1940 and was used widely during World War II and the Korean War. Hessian Matting, developed by the Canadian Army Engineers, was also introduced around the same time. It was significantly different, in that is was composed of a bitumen impregnated burlap used primarily as a waterproof cover to a mechanically-stabilized base surface. Square Mesh Track (SMT) was produced in rolls and consisted of heavy wire material joined together to form three-inch squares. SMT was used to form light- and medium-weight aircraft runways and operation areas. It was a lightweight material that could be unrolled quickly. All of these systems proved successful in their own specific application areas. However, they were not effective for heavier fighter and bomber aircraft developed during and after the Korean conflict (Dover et. al., 2002).

The U.S. Army Engineer Research and Development Center (ERDC), known at that time as the U.S. Army Engineer Waterways Experiment Station (WES), was one of the key organizations tasked by the U.S. Air Force, beginning in early 1945, to develop replacement airfield matting systems. The goals were to provide stronger matting systems to support the growing weights of fighter and bomber aircraft and more durable mat systems with longer operation times and the potential for reusability. Mild steel plank mats, such as the M6 and M8 (Photos 2 and 3), were initially the best solution.

These steel mats were modified versions of the original PSP, with single wheel load carrying capabilities of 16,783 and 22,679 kg (37,000 and 50,000 lb), respectively. In July 1954, the WES began testing experimental matting systems employing a new material, magnesium alloys. The newer T7 (Photo 4) magnesium mat, unlike its traditional steel counterparts (M6 and M8), was about half the weight per unit area, and

offered tensile and compressive strengths of 30 percent and 50 percent higher, respectively (Garrett and Horsley, 1957).

Photo 1. Pierced Steel Plank (PSP) mat

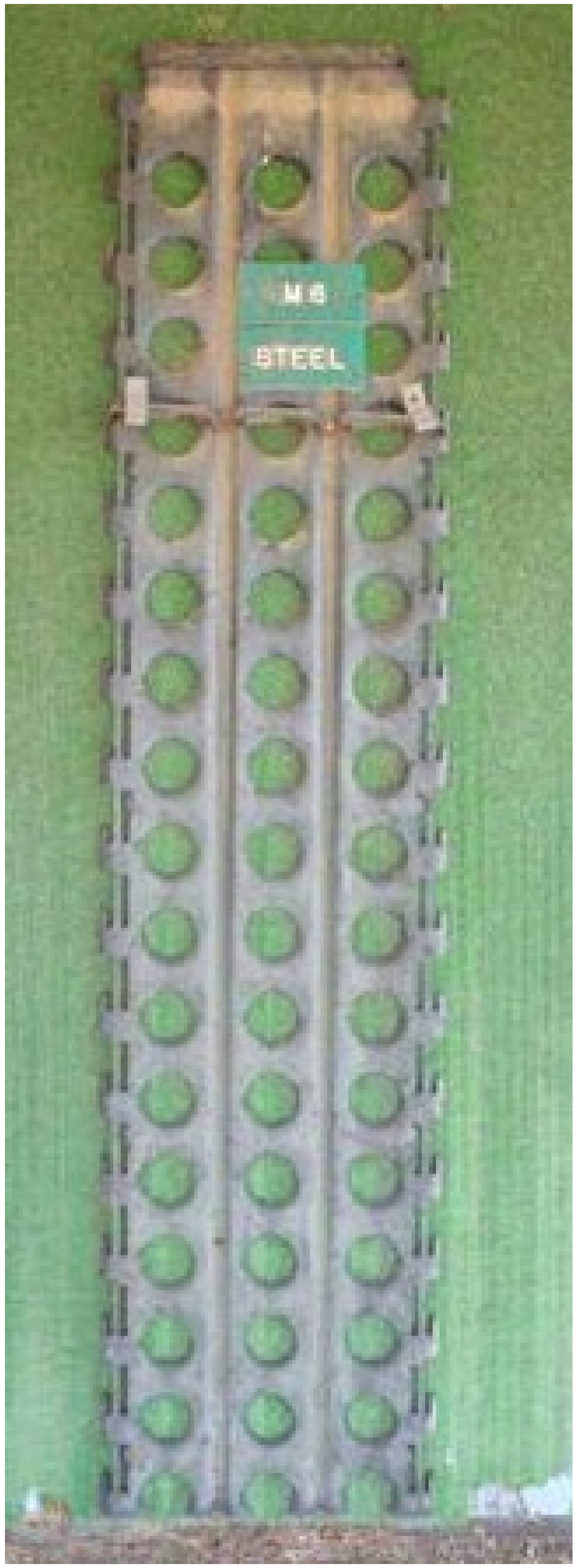

Photo 2. M6 mat

Photo 3. M8 mat

Photo 4. T7 mat, note the cross section bolted under the mat label

Traffic tests of the T7 matting were performed in 1954 at both the Engineer Proving Grounds at Fort Belvoir, Virginia and the WES in Vicksburg, Mississippi. The Proving Grounds performed all tests outdoors, exposed to weather elements. The WES full-scale traffic tests were performed in the Hangar 4 Pavement Test Facility (Photo 5).

Photo 5. Hangar 4 Test Facility at ERDC in Vicksburg, Mississippi in 2007

This facility is still in use today and provides a large covered area for test sections. Test sections in the facility have limited exposure to sunlight and are isolated from inclement weather such as rainfall. As a result, soil moistures, a critical parameter in test section work, can be controlled. A test section 37.2 m (122 ft) long and 12.8 m (42 ft) wide was constructed. This section was constructed to compare performance of the

T7 matting system to that of the M6 and M8 systems. The subgrade was a fat clay (CH) with a liquid limit and plastic index of 60 and 39, respectively. The subgrade was placed at a moisture content of 20 to 23 percent, depending on the test item, and constructed to a final depth of 56 cm (22 in.) with a finished California Bearing Ratio (CBR) strength of 6 to 11.

Traffic was applied using a load cart equipped with a single aircraft wheel (size 56×16) inflated to 1379 kPa (200 psi) and loaded to 22,679 kg (50,000 lb). Traffic was applied by driving the load cart across the section in a forward/backward motion. The cart was maneuvered to shift the wheel path one tire width on the backward trip to the starting position.

Data collected at both the Vicksburg and Virginia sites during and after traffic included the following:

- Soil density,
- Soil moisture content,
- In-place California bearing ratio (CBR), and
- Mat deflections under wheel load.

In conclusion, the WES section provided a more objective comparison of the matting performance because in the covered facility subgrade properties did not vary significantly from the required CBR of 6 to 11. The original plan of test required that the Fort Belvoir site first conduct mat testing at a CBR range of 11 to 17, with additional testing performed at a CBR range of 6 to 11. However, approaching winter weather halted the testing of the lower CBR range. The WES section was constructed to fill this gap in information. The WES section stayed within or below the CBR tolerance of 6 to

11 on all test items, with most items maintaining a range of approximately 5 to 8 CBR. In contrast, most of the Fort Belvoir test items were near the top of their required CBR range of 11 to 17, with almost half of the test items above a CBR of 17 (Garrett and Horsley, 1957).

In mat testing, it is critical to construct the subgrade to and maintain a set range of CBR strength throughout traffic application to obtain information on a matting systems capability. If the test section is not properly constructed and moisture content is not properly controlled properly throughout the testing, the strength of the section can increase with time, primarily due to drying of the soil. The drying of the soil generally results in an increase in strength (CBR) and more favorable test results with the progression of traffic.

In WES testing, T7 demonstrated better performance than the M6 and M8 systems tested. In addition, more of the T7 components could be reused and the T7 mat was very practical to produce.

In the following years, several additional matting systems and modifications of the same systems were developed (Burns and Barker, 1966; Brabston, 1967; Green, 1967; White, 1971). In 1965, the U.S. Air Force introduced AM2 matting (Photo 6) into its inventory. In the fall of 1966, the WES initiated tests of the Harvey Aluminum Co., Inc. two-piece version of AM2 matting.

The AM2 matting was, at that time, produced by several different vendors under different procurement contracts. The WES was tasked with testing small lots of the AM2 from different manufacturers to determine if each vendor’s product was capable of supporting a 60,000-lb gross weight aircraft (Brabston, 1967).

Photo 6. AM2 matting bundled for shipment

Traffic testing for the AM2 matting system was conducted with the following condition:

- Three fat clay (CH) test sections (3, 6, and 10 CBR),
- One test section of loose sand,
- Simulation of 27,215-kg (60,000-lb) gross weight aircraft:
  - Single-wheel load cart,
  - 12,246-kg (27,000-lb) load,
  - 2,758-kPa (400-psi) tire pressure,
- Test section dimensions: 45.7 m (150 ft) × 7.3 m (24 ft), and
- Traffic applied to a 3-m (10-ft) wide traffic lane.

The load conditions were based on the larger, heavier fighters of the day, such as the McDonnell-Douglas F-4 Phantom aircraft.

The same data recorded during the T7 mat testing described above was recorded for the AM2 tests. Constructing and maintaining constant subgrade conditions (moisture and density) was critical. Table 1 shows a summary of the condition of the four different test section items before and after traffic. The before and after values shown in the table are averages based on the original table values. These averages utilized three test results (at 0, 6, and 12 in. of depth) for each test item.

Table 1. Summarized Results by Burns and Barker, 1966

			Before Traffic			After Traffic		
Test Lane	Test Item	Reqired CBR	Moisture Content (%)	Dry Density (lbs/cu ft)	Avg CBR	Moisture Content (%)	Dry Density (lbs/cu ft)	Avg CBR
1	1	3	29	92	2.9	27	94	3.6
	2	6	25	97	4.8	25	98	4.9
	3	10	23	99	10	23	101	11
	4	**	10	103	3.7	7	113	43
2	1	3	29	92	2.9	29	93	3.6
	2	6	25	97	4.8	28	99	5.4
	3	10	23	99	10	23	101	10
	4	**	10	103	3.7	7	108	36

** = No CBR target value was assigned for this "loose sand" test item.

As seen in Table 1, average CBR values were at or within 10 to 20 percent of target value. It is always more conservative in the evaluation of matting systems to be at or below the subgrade target CBR value because lower soil strengths will result in fewer passes across the mat before failure. In comparing values before or after traffic, it is clear that the strength of the test section was well controlled, and the after-traffic values of CBR were still at or below the target with the exception of Test Lane 1, Test Item 3, and Test Lane 2, Test Item 1, both of which were close to the target. Results of the Harvey AM2 tests showed the product was acceptable, having sustained a minimum of

3,200 passes of the load cart over all test items, with predicted pass levels rising as the CBR strengths increased

With technological advancements in plastics, resins, and reinforcing materials, new mat designs were developed. This occurred at the same time AM2 matting was being stockpiled in military inventories. There were several variations of these new composite mats. One example is the T14 mat (Photo 7) introduced around 1965 (Green, 1967). This new mat was a sandwich-type structure with a core of high-density, foam reinforced with epoxy resin and glass fibers. This core was sandwiched between filament-wound, glass-fiber facings impregnated with polyester resin. The mat had extruded aluminum side and end connectors secured by a filament winding process. The use of composite mats, such as the T14, was desirable, as it was anticipated to provide a comparable product to AM2 in performance, with less weight and logistical requirements and less demand on metal supplies.

WES was tasked with the evaluation of T14 matting in 1967 (Green). Design criteria for this testing included:

- Test section dimensions: 12.2 m (40 ft) × 7.3 m (24 ft),
- 61 cm (24 in.) of fat clay (CH), with CBR = 4,
- Single-wheel load cart, 1,724 kPa (250 psi) tire pressure, and 11,340 kg (25,000 lb) load.

The clay used in the construction of the test section was required to have an average liquid limit of 58 with a plasticity index of 33. The section subgrade was compacted in lift thicknesses of 15.2 cm (6 in.). Each lift was tested for moisture content, CBR, and density. Average CBR values of 3.7 to 3.9 (target value was 4) were obtained on the

section. Traffic was applied in a normal fashion, with most of the traffic confined to a 60-in.-wide lane located in the middle of the matting installation. Matting deflection and permanent deformation (rutting) were determined as the traffic progressed (Green, 1967).

Photo 7. T14 mat

The average CBR values after traffic were between 4.1 and 5.2. Much of this increase in CBR was attributed primarily to consolidation of the clay beneath the mats as they began to fail, based on measurement of moisture content and CBR levels before and after traffic. This matting system was considered failed after only 12 coverages of traffic. The T14 matting failed to meet the minimum performance standards and was not recommended for field testing or application.

Testing and evaluation of new or modified matting systems continued at the WES through the end of the 1960s, that is through the Vietnam War, and into the early 1980s. Mat testing work at WES was sparse through the remainder of the 1980s and early 1990s. The work to test and evaluate matting systems was revived in the 1990s at WES. In a new focus, a program was initiated to determine what new mat technologies could be used to expedite vehicular traffic over soft, sandy soil environments in particular, for logistics-over-the-shore or beach landing operations (Webster and Tingle, 1998). This work continued with further research on expeditious road construction over soft soils, like sands and silts (Santoni, et. al., 2001). Additional studies were conducted in logistics-over-the-shore operations by Santoni in 2003.

The current program initiated in 2002, under which this research is conducted, is the Rapid Maximum-On-Ground (MOG) Enhancement work unit of the Joint Rapid Airfield Construction (JRAC) program. This particular work unit addressed the need for a rapidly installed helipad utilizing systems lighter and less costly than the traditional AM2 at a forward operating base (FOB). Between 2002 and 2004, work was focused on rapid construction of parking aprons and taxiways for fixed wing aircraft using commercially-marketed matting systems. This first phase of research was focused on operations of the

C-130 transport aircraft. The final phase of the work unit and the focus of this thesis is on matting systems for operations of the C-17 transport aircraft.

Modeling Matting System Response to Loading

Introduction

From the above discussion, evaluation of matting system performance, especially at the WES, has used an empirical approach. In the empirical approach, a full-scale test section (soil section) at a specific strength (CBR) is built and overlaid by one matting system. Traffic is applied to failure. From a series of such tests where the test section subgrade strength is varied, a family of curves describing the performance of the matting system can be formed. To build a catalog of different matting system curves, the same procedure must be repeated for each matting system.

Full-scale testing provides realistic measures of performance under controlled conditions. The alternative would be to use traffic of actual aircraft on an airfield, which is costly, and provides poor control of the test variables, such as soil moisture, compaction, aircraft wheel position, and traffic control. Full-scale test sections provide for control of the test variables. However, even with the savings realized from the use of full scale test sections, it is not a low-cost option.

Modeling matting systems can provide a low-cost, “first-cut” evaluation method, especially when a new prototype system is to be evaluated. It is important the model be “calibrated” using a set of existing empirical data. Calibration provides a measure of how well the model can predict the desired response or performance. If the model’s predictions are reasonable, the model can be used to evaluate a matting system’s

capabilities and if full scale test section efforts are warranted. In addition, a parametric study utilizing the model can help in planning for the test sections. This combining of models (mechanistic) with full-scale test section data (empirical) is called mechanistic-empirical testing.

Efforts to determine the use and validity of models for matting system evaluations have been limited in the past. As is evident from the discussions of full-scale testing, the primary approach in testing matting systems has been use of full-scale test sections. It is reasoned that this purely empirical approach was typically used in the past for several reasons:

- Matting system modeling is a complicated task,
- Complex mathematical modeling equations were difficult to solve,
- Computer capabilities to solve such equations were limited until the 1960s,
- Test sections, while somewhat costly and time-consuming, offered simple and straightforward answers, and finally,
- There was a lack of understanding of application of models to mats.

State of the Art in 1971

A study (White, 1971) was conducted involving the theoretical analysis of landing mats using several models developed to analyze either the landing mat-soil structure, pavement-soil structure, and/or layered problems. His focus was to evaluate the use of five modeling systems and determine if they could accurately predict the response of a matting system to aircraft traffic when installed over a given strength base soil.

The five models included in the study were the Purdue landing mat-variational foundation model, the Shell N-layered model, the Chevron N-layered model, the

University of Texas beam-slab model, and the finite element method. Although a full explanation of each model is outside of the scope of this presentation, Table 2 summarizes characteristics of each model and a general explanation of each follows.

Table 2. Models Examined by White, 1971

	Purdue Model	Shell N-Layered Model	Chevron N-Layered Model	U of T Beam Slab Model	Finite Element Analysis
Homogenous, Elastic, Isotropic Layers	x	x	x	x	x
Can Model Single-Wheel Loads	x	x	x	x	x
Can Model Double Wheel Loads	x	x	x	x	x
Can Specify Layer Interface (rough, smooth, etc)		x			x
Number of Layers Capable of Modeling	2	11	15	2	>15
Number of Loads Capable of Modeling	1	30	1**	1	1

** It was determined that by using the Principle of Superposition, multiple loads could be analyzed.

The Purdue model was developed by researchers at Purdue University under a contract with WES (White, 1971). It represented the landing mat-soil structure and predicted the useful life of the matting installation. This is a feature unique to the Purdue model among the models examined. The Purdue model was based on a solution for elastic foundations (Vlasov and Leont'ev, 1966). This model uses a foundation that is assumed homogenous, elastic, isotropic, and has a compressible layer of thickness H over a rigid base. There is considered to be no slip at the interface of the base and foundation. The mat is represented as an infinite beam on the foundation. This beam maintains contact with the foundation and uses the flexural rigidity (EI) of the mat for modeling. The Purdue model is capable of simulating both single- and dual-wheel loads using a superimposed beam load of infinite length that maintains total contact with the mat.

The Shell N-layered Model was developed to examine layered theory. At the time of White's work, the Shell model was capable of modeling up to 11 layers, each semi-infinite and three-dimensional and all consisting of ideally elastic, homogeneous, and isotropic materials. The layers were all assumed to be of uniform thickness and stratified over a semi-infinite foundation. The interface between layers could be designated as smooth or rough. This model was capable of simulating as many as 30 individual loads, each applied as a vertical stress over a circular area. In general, the size of the problem that could be solved was limited by computer capacity and dimensioning statements (White, 1971).

In using the Shell N-Layered Model to simulate mat systems on a soil base, White disregarded the mat's horizontal shape and represented the mat and soil base as two elastic, homogenous, isotropic materials in layers over a third semi-infinite foundation. The moduli of the mat and soil base were required to execute the model analysis (White, 1971).

The Chevron N-layered Model was developed by the California Research Corporation to analyze N-layered systems similar to those of the Shell model. This model used the same assumptions and layered system as the Shell N-Layered Model, described above, but this model was capable of analyzing up to 15 layers at a time. This model was limited to a two-dimensional case; however, so only one wheel load at a time could be applied to the system. White did determine that, using the principle of superposition and some additional computer code, the effects of multiple-wheel loads could be examined with this model (White, 1971).

The University of Texas Beam-Slab Model was developed to solve a variety of problems. White used the form of the model that was designed to analyze concrete slabs in a configuration designated as a beam-slab program (DSLAB-5). The model was described as a system of horizontal x-y beams connected at their nodes by elastic blocks that account for Poisson's Ratio. The stiffness of the structure is represented by assigning stiffness values to the x-y beams. The torsional stiffness is represented with torsion rods connecting the midpoint of parallel beams. Elastic springs supporting the nodes represent the soil foundation. Mat joints were represented by assigning an 85-percent beam stiffness value at the joint locations. This model did require some assumptions to be used for the analysis of mat modeling, and the application of a wheel load had to be modeled as a concentrated load at a node (White, 1971).

The Finite Element Model (FEM) is a diversified numerical method that can be used to analyze structural and continuum problems with a variety of material properties and boundary conditions (White, 1971). The model that White used only made elementary use of the available FEM theory and its correlations for complex materials. The model utilized the E values of both the subgrade and mat materials. Loading was axisymmetric and applied uniformly over one-half of the tire print.

Of the five models examined, the Purdue model was the most applicable to mat modeling, but in its form studied by White, the model was only applicable to single-wheel loading, and further work was needed to make this model applicable to dual-wheel loadings. The Shell and Chevron models were limited in their ability to accurately model landing mat-soil structures. The Texas model, available in a better version at the end of White's work, showed promise to be applicable to the mat modeling

application, but this new version was never examined. Finally, the FEM had some application in the modeling of mats in that it could account for a wide range of mat foundation soil properties that the other models examined could not. White recommended further work in the use of the FEM for mat modeling.

In his conclusions, White pointed out that mat modeling was a complex problem. The Purdue model examined showed great promise in being able to simulate a matting system, but it needed further research. He suggested further research with the FEM, which at the time, had just been upgraded to a three-dimensional capability. White's work was some of the first to closely review the potential of such models to adequately simulate loads and stresses in matting systems. Today, similar models still offer the best opportunity of simulating pavement matting systems. In that regard, discussion of the more recent work with these models and some of the more recently developed models is in order.

Layered Elastic Analysis Models

Several of the modeling systems investigated by White and described earlier in this section could be classified under the general term of layered elastic analysis models (Shell and Chevron N-Layer and the Purdue Model). The original theories of layered elastic analysis are credited to V. J. Boussinesq who published the work in 1885. Many variations have come about using the theories, as evidenced above. One is WinJULEA. The original code was developed by Dr. Jacob Uzan of the Technion at Haifa, Israel. The code was modified by the then Waterways Experiment Station and Dr. Uzan to increase accuracy and simplicity of use. That modification resulted in JULEA (an acronym for

Jacob Uzan Layered Elastic Analysis), which was later converted into a Windows-based program, thus the prescript "Win" (Barker and Gonzalez, 1991).

Assumptions imposed on the theory underlying WinJULEA are:

- Horizontally, the pavement system is considered a continuum (no joints),
- Layers extend horizontally to infinity,
- Bottom layer extends to infinity in depth,
- All layers are elastic, isotropic, and homogenous,
- Loads are applied as circular areas of uniform pressure,
- Loads applied are static, and
- All layered materials are described by modulus of elasticity (E) and Poisson's ratio (ν).

WinJULEA offers a simple modeling system for flexible airfield pavements. It is capable of handling up to 15 layers and any number of wheel loads. Stresses, strains, and deflections are computed at any point in the system and at any depth. The layer interfaces can be fixed, frictionless, or be assigned some value in between the two. As a Windows based program, WinJULEA is user friendly and produces solutions fast.

Modeling Slabs with Joints

The ability of jointed concrete pavements to transfer load from one slab to the next has been studied for many years (Westergaard, 1948; Skarlatos, 1949; Gonzalez and Barker, 2005; Wang, et. al., 2006). Professor Westergaard first introduced his concrete slab theories in the 1940s (Westergaard, 1948). It was these slab theories on which the U.S. Army Corps of Engineers (USACE) based its method of analysis and design of airfield concrete pavements which are still in use today. Westergaard devised equations

for solution of stresses and deflections due to single wheel loads near the edge of a concrete slab. These formulas were extended by Pickett and Ray (Pickett, 1951) to the case of multiple-wheel loads. The USACE computerized these solutions and has been using this approach for the design of concrete pavements and the analysis of aircraft loading near the edge of pavements for the past 60 years (Gonzalez and Barker, 2005).

Gonzalez and Barker (2005) conducted a study to review the work by Skarlatos under the supervision of Westergaard (1949). In this work, calculation of stresses and deflections in concrete pavements due to aircraft loadings was examined, with the slabs connected by elastic joints. With the similarities of concrete slabs on a base course and matting systems on a soil foundation, the Skarlatos model offers a close simulation of concrete slab systems and in turn, offers a potential system for mat analysis.

As discussed above, the Westergaard stress equations facilitated the implementation of analytical and design procedures still used today. However, these equations did not account for load transfer across the joints. Load transfer from one slab to another reduces the maximum stresses in the slab near the joints. Studies by Hutchison (1966) at the Ohio River Division Laboratories (U.S. Army Corps of Engineers, Cincinnati, Ohio) showed that load transfer devices such as keys, dowels, and aggregate interlock provide a minimum of 25 percent transfer across joints. However, there are many instances where this assumption may not fully apply, such as poor joint construction, joint movement due to high temperature differentials, rapid joint deterioration, and others. In these cases, a better prediction is needed (Gonzalez and Barker, 2005).

In 1950, Skarlatos, in a contract report to the USACE (Skarlatos, 1949), described a general solution for the calculation of the stresses and deflections on concrete slabs connected by elastic joints (Figure 1), where Q is the load $\bar{x}$ and $\bar{y}$ are the coordinates of the calculation point. The solution uses a "stiffness coefficient" of the joint between the slabs to calculate the stresses and deflections on loaded and adjacent slabs. This "stiffness coefficient" measures the ability of the joint to transfer shear forces. Much of this work by Skarlatos remained unused for many years, probably due to the complexity of the equations, with only a small set of the equations solved for single-loaded areas. With the advent of faster computers, these complex equations are now easier to solve. The simplicity of the Skarlatos solution is of great interest to the USACE. It offers a more simple solution than the more publicized two- and three-dimensional FEM solutions (Gonzalez and Barker, 2005).

Assumptions associated with Skarlatos' solution are:

- Slabs are elastic, isotropic and of uniform thickness,
- Subgrade reaction (k) is vertical load divided by the vertical deflection due to the load,
- The ordinary theory of bending of plates or slabs is applicable,
- Slabs are assumed to be large and load is applied close to one joint or edge, with other joints assumed far enough away to have no influence,
- Joints are elastic, continuous, and capable of transferring load from one slab to the next by vertical shear without bending moments across the joint.

Skarlatos' solution for stresses and deflections is applicable for any location on the loaded and adjacent slabs when a single concentrated load is applied. By using the

principle of superposition, this solution was extended to multiple uniformly-loaded elliptical areas, such as an aircraft wheel (Figure 2).

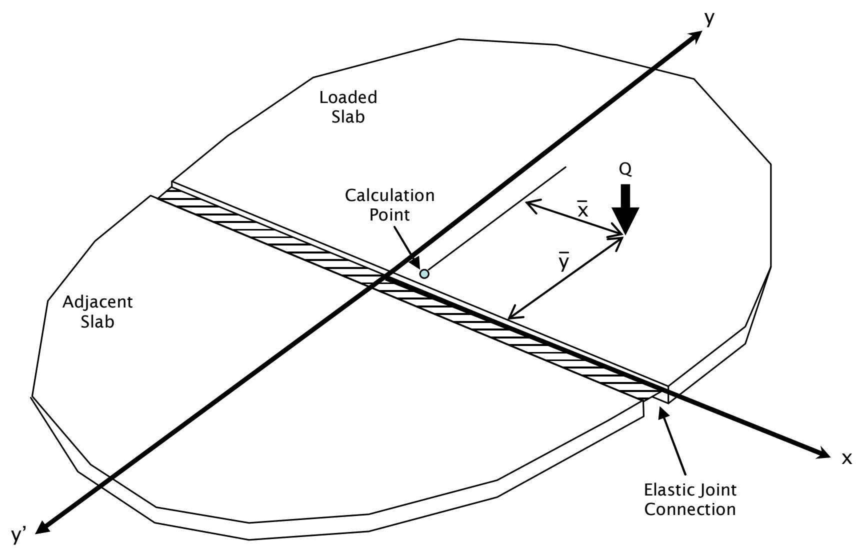

Figure 1. General geometry and loading condition for the solution of deflections and stresses of jointed concrete slabs (Gonzalez and Barker, 2005)

Gonzalez and Barker examined two data sets to determine the validity of the Skarlatos approach to calculating stresses and deflections. The first data set was collected from tests on small-scale slabs conducted by the Ohio River Division Laboratories of the Corps of Engineers in 1955. The second data set was produced by the USACE in field strain and deflection measurements under F-15 aircraft single-wheel load 13,600 kg (29,982 lb) at the Denver International Airport. In their summary, Gonzalez and Barker stated:

- The Skarlatos solution and the extensions to multiple wheel loads compares favorably with the predictions made by Westergaard equations using small concrete slabs.

- The Skarlatos solution reasonably predicts deflections and load transfer efficiencies.

- The computer program for the solution is simple and is an efficient way of analyzing concrete pavements with different joint efficiencies.

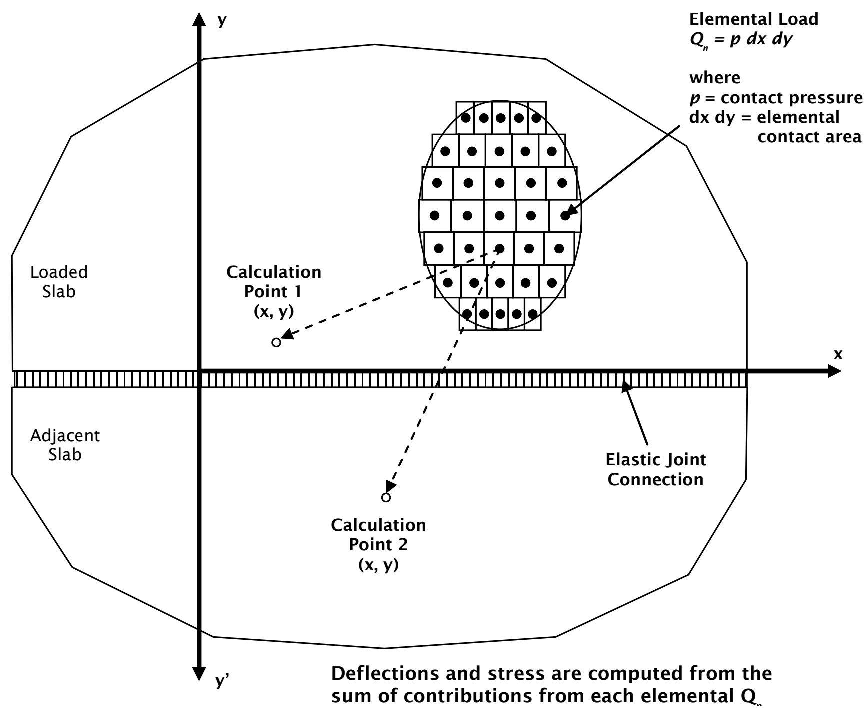

Figure 2. Extension of the point load solution to an elliptic-shape loaded area implemented in the solution of deflections ands stresses (Gonzalez and Barker, 2005)

Single Plate With Free Edges

In late 2006, a review and revival of the original work by Glenn Murphy (1935) to develop a model that is described as a finite plate on an elastic foundation was conducted. The model, originally developed in 1937, was translated into computer code by Gonzalez and Barker (2007) of the U.S. Army Engineer Research and Development Center (ERDC) in Vicksburg, Mississippi.

Glenn Murphy published a report (1935) on a method of determining stresses and deflections in rectangular plates supported on elastic foundations, with particular reference to plates that deflect free of the foundation under the action of loading. This is of particular interest in the area of mat applications. As a matting system is subjected to rolling traffic loads, the underlying soil deforms and ruts. With continued traffic, there is an uplift of the matting on both sides as a wheel load moves along the mat. The uplift is usually small, but the capability to model this action could provide a more accurate model for the mat system.

Assumptions associated with Murphy's model include:

- plate is horizontal, loads are vertical,
- deflections are small in comparison to the plate thickness,
- plates are homogenous, isotropic, and elastic, and
- The subgrade reaction (k) is proportional plate deflection.

Gonzalez and Barker reported good agreement between predicted results of this model and that of Westergaard and Skarlatos. There is some concern over the validity of this model when applied to a thin airfield mat. As Murphy stated, the deflections of the plate are considered small as compared to its thickness. This could present issues with airfield mats being between one and four inches in thickness and observed deflections in the field of as much as three or more inches.

Finite Element Modeling

A more recent model is ISLAB2000. This two-dimensional FEM program was developed by ERES Consultants, Inc. as a modern version of the ILLISLAB program

developed in 1977 at the University of Illinois at Urbana-Champaign for the Federal Aviation Administration. The basic features of this program include (Wang et al., 2006):

- Concrete slab model,
- Elastic and homogenous slabs,
- Winkler foundations,
- Models one or two layers over the foundation,
- Layer boundary interaction can be varied,
- Can model partial slab contact with foundation,
- User-defined number of slabs,
- Multiple wheel and axle loads,
- Rectangular loading area, and
- Can model load transfer.

This program offers easy input of data and a user-friendly display of the model results is also provided. Because of its many capabilities, it could prove a good model for mat systems. It does have a few limitations when used in concrete slab analysis. These include difficulty modeling concrete with joint reinforcement and continuously reinforced systems and only being capable of modeling two layers and a foundation, among others. The model does offer the feature of being able to simulate partial contact between the slab and the subgrade. As explained in the discussion on the Murphy model above, this can be a key parameter to consider. This feature could allow an even better "snapshot" of mat response, especially on soft soil foundations.

Another finite element program, JSLAB2004, was originally developed by the Portland Cement Association. Like ISLAB2000, it is based on a 2-dimensional finite

element model with the same assumptions and features as listed above. There are some differences between JSLAB2004 and ISLAB2000, including the following (Wang et al., 2006):

- Even easier input mechanisms for data,
- Library of axle and vehicle configurations,
- Can calculate response-time history using step-moving loads, and
- 3 × 3 slab configurations are the largest that can be analyzed.

EverFE 2.23 is a three-dimensional finite element model (FEM) developed at the University of Washington for the Washington Department of Transportation (Wang et al., 2006). EverFE is a typical FEM program that provides ease of use and three-dimensional visualization of solution stresses and displacements. Other features offered by EverFE that are not available on ISLAB2000 or JSLAB2004 include:

- Either Metric or English units,
- Up to three layers can be modeled,
- Variations in joint opening can be modeled, and
- Perpendicular or skewed transverse joints are allowed.

As with any model, EverFE also has some limitations. Because it has more capability and can handle larger systems of slabs, the computation time with this program is larger than with the 2-D systems like ISLAB2000 and others, especially if a very fine mesh is used. As with JSLAB2004, the number of slabs that can be analyzed is limited to a 3 × 3 configuration.

Wang et al. (2006) compared the three models described above (ISLAB2000, JSLAB2004, and EverFE 2.22). Wang focused on the ability of these models to predict

response in jointed plain concrete pavements and compared the computed responses to the computed solutions by Westergaard's methods (1948) as well as full-scale, measured test section responses.

Wang et al. (2006) concluded the following:

- ISLAB2000 offered the lowest percentage relative deviation of peak predicted responses from corresponding measurements (deflection and strain) at 16.2 percent, JSLAB2004 and EverFE 2.22 produced 17.6 percent and 22.9 percent, respectively,

- Either ISLAB2000 or JSLAB 2004 can be reliably used in the analysis of rigid pavement primary responses,

- Both of these models require less time and effort to run, when compared to EverFE 2.22, which could be a factor for first-elimination evaluations,

- Even though 3-D models like EverFE 2.22 offer some advanced capabilities, it was found that the differences between 3-D and 2-D model results were small,

- Exactly identical results between three finite element models should not be anticipated, even when the basic theory and many times the equations and methodologies, are the same, and

- All three models produced close approximations to the Westergaard solutions.

Even when the analytical methods within programs are nearly identical, small differences can lie within the details of each program. Coding issues such as nonlinear problem solutions, approximations, systems of number rounding, and others can all affect the answer given by several models to a single problem scenario (Wang et al., 2006).

The above is a limited review of a large number of empirical and mechanistic models developed by many researchers over the last 60 or so years. Further analyses and development of these models is needed to allow more accurate modeling of matting systems on soft soils. Some of the models discussed can approximate mat system initial

response and therefore offer some ability to predict initial performance, but there is a need for more exploration and discovery in this realm.

CHAPTER III

FIELD TESTING AND EVALUATION

Introduction

The Rapid Maximum-On-Ground (MOG) Enhancement Technologies project of the Joint Rapid Airfield Construction (JRAC) program was tasked to evaluate available matting systems for use in the expansion or addition of taxiways and parking aprons at austere, forward-located airfields. To perform this evaluation, full-scale test sections were constructed at facilities located at the U.S. Army Engineer Research and Development Center (ERDC) located at the Waterways Experiment Station in Vicksburg, Mississippi. Several matting systems were examined, performance data was collected, and final conclusions on the mats and their application in a JRAC scenario were formed.

This is the second phase of the Rapid MOG Enhancement Technologies project within the JRAC program. The first phase of this effort examined matting systems for rapid MOG enhancement of C-130 transport aircraft facilities. This second and final phase examined matting systems for use with the larger C-17 transport aircraft.

Final evaluation of this second phase of research was conducted in a live demonstration in northern Australia. This demonstration included the construction of an unsurfaced runway to handle C-17 aircraft, two aprons for C-17 aircraft, and associated connector taxiways. The demonstration involved operations and parking of one C-17 aircraft. The initial plan was to build one apron using a matting system. However, due to

costs and logistics, this plan was cancelled. In order to include the mats in the exercise, they were used to build a large helipad, mainly to demonstrate the assembly of the system and provide a display of the product. The ultimate goal of this study and the one prior to it (C-130 aircraft) is to provide design and performance guidance for matting systems and materials used to rapidly increase the MOG capacity of a contingency airfield.

C-17 Aircraft Test Sections

Discussion of Test Plan

This research effort is to focus on evaluation of matting systems for rapid expansion of taxiways and parking aprons at austere airfields for C-17 transport aircraft. Matting systems included in the study were selected based on final results of the first phase of this research project (Anderton and Gartrell, 2005) in which matting systems were evaluated for the C-130 transport aircraft.

For each mat system, subgrades with low strength (5 to 6 CBR) and medium strength (8 to 10 CBR) were prepared. These levels of strength are based on current United States Air Force (USAF) criteria (AFCESA, 1997, ETL-97-9). These strength levels were further verified by ERDC’s experience with soils and JRAC’s research of predicted soil types that could be encountered on austere airfields world wide.

Unlike the first MOG test section (Anderton and Gartrell, 2005) a high soil subgrade strength with a target CBR of 40 to 50 was not included, as the C-130 load cart tests showed that this high strength soil requires little if any modification in order to obtain the pass levels required for a USAF or JRAC application. Aspects such as mat weight, ease of assembly, durability, strength, and logistical footprint were all examined

during these test section analyses. In addition, a range of instrumentation gauges were installed during construction of the medium-strength test section to collect mat stress and strain data. This data would be a resource to validate potential models of matting/ subgrade systems. A brief examination of the instrumentation and examples of the data gathered will be discussed. This thesis will also make use of some of the data in modeling analysis of some of the matting systems evaluated for the C-17 aircraft.

Test section traffic occurred between March 2005 and August 2006. All test section construction, trafficking, and data collection were performed by personnel of the ERDC at the Hangar 4 Pavement Test Facility in Vicksburg, Mississippi. Material for the test sections included locally available high plasticity (CH) "buckshot" clay for the low strength subgrade, and a silty-sand (SM) blend developed at ERDC for the medium strength subgrade. This blend resembles the silty-sand found at Fort Bragg, North Carolina, during the first JRAC demonstration, and is characteristic of the silty-sand material found over a large percentage of the Earth's surface. The various mat systems used for the testing program were provided by product vendors.

Materials

The first test section (CBR 8 to 10) consisted of a silty-sand (SM) blend. This blend consisted of a mixture of 13 percent river sand and 87 percent silt, based on samples of the silty-sand material collected during the first JRAC demonstration at Fort Bragg, North Carolina, in 2004. Table 3 and Figure 3 through 4 below detail some of the properties of the blend, including compaction curves of the blend, using both standard effort (ASTM D 698) and modified effort (ASTM D 1557).

Table 3. Baseline Data for SM Blend Material

SM Blend Formulation Data:		
Approximate % Content by Soil Size		Approx. Gs
Gravels	0	2.41
Sands	87	2.66
Fines	13	2.73
Approx. Gs of silty sand blend =	2.67	

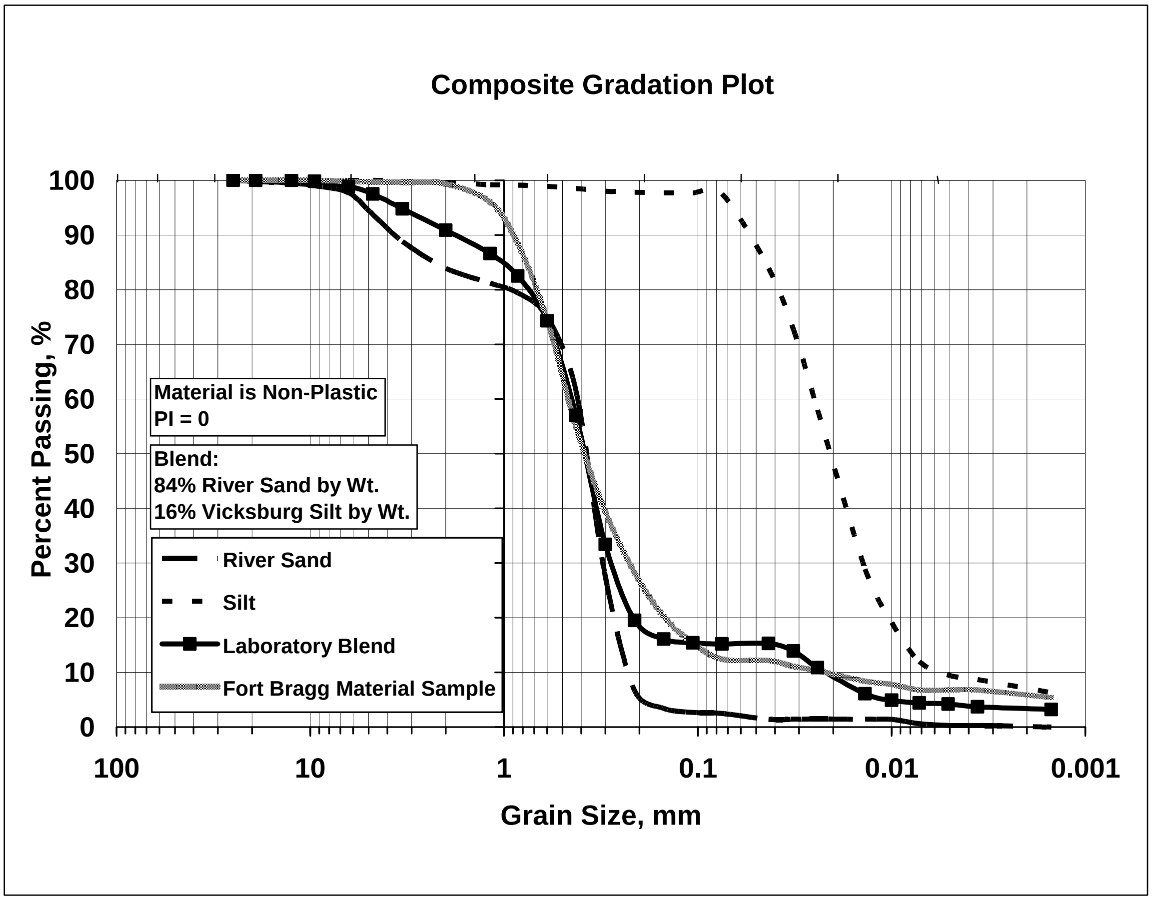

Figure 3. Gradation Curves of SM Blend Material

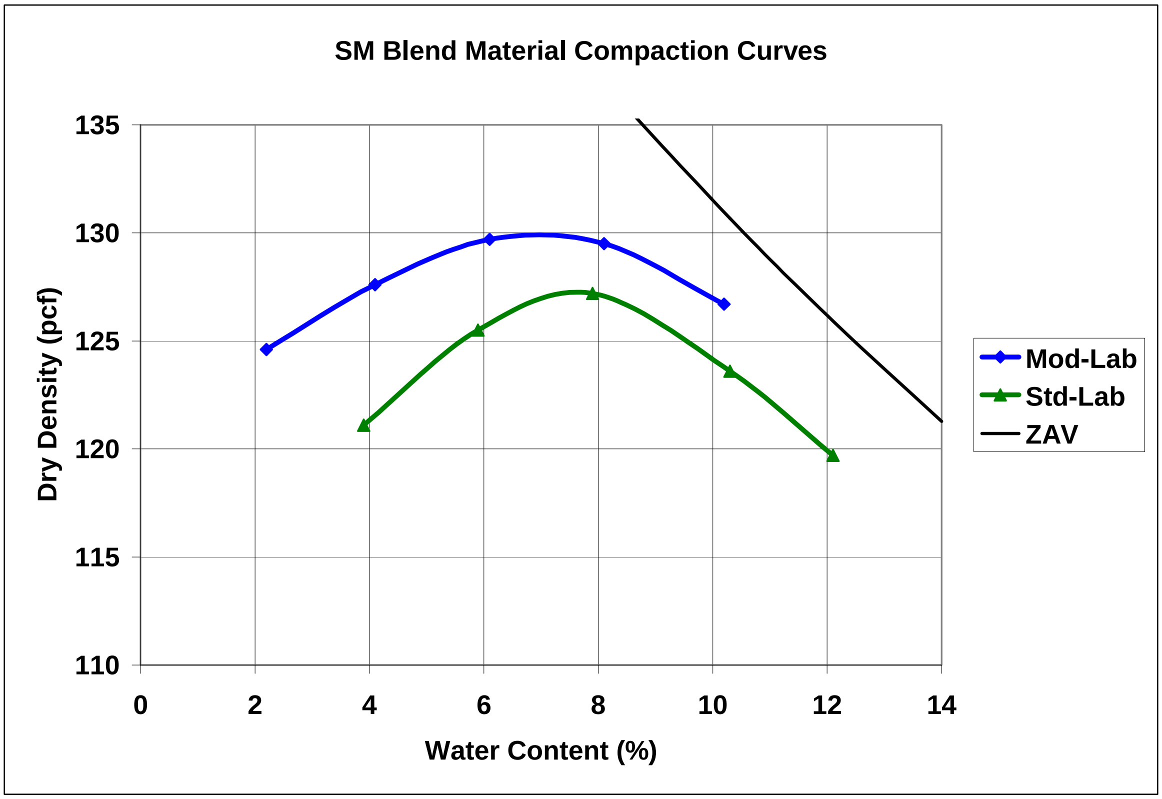

Figure 4. Compaction curves for the SM blend material

The low strength (5 to 6 CBR) test section was constructed of high plasticity clay (CH) material, locally referred to as "buckshot" clay. This material was chosen because of its local availability, low cost, and the extensive experience with this material that exists at the ERDC. This material is naturally occurring in the Vicksburg, Mississippi, area. Properties for the CH material are shown in Figure 5.

The mats chosen for testing were commercially available products that passed and were approved as JRAC capable products during the first MOG work unit (C-130 aircraft). The assumption was any matting system previously tested not meeting the criteria for the lighter C-130 aircraft traffic would not survive the C-17 aircraft traffic. No additional matting systems were added to the test plan. It was understood that not all of

these products would pass the first round of tests (medium-strength subgrade), and it was estimated that perhaps only two of three of the products would survive tests on the low-strength subgrade. Tests were conducted on:

- DURA-BASE®
- BRAVO® Mat
- ACE-Mat™ (5-Ply)
- Unsurfaced Control

Atterburg Limits:		Other:	
Liquid Limit (LL) =	**76**	Specific Gravity =	**2.74**
Plastic Limit (PL) =	**24**	%Clay (<0.005 mm)=	**45.4**
Plasticity Index =	**52**		

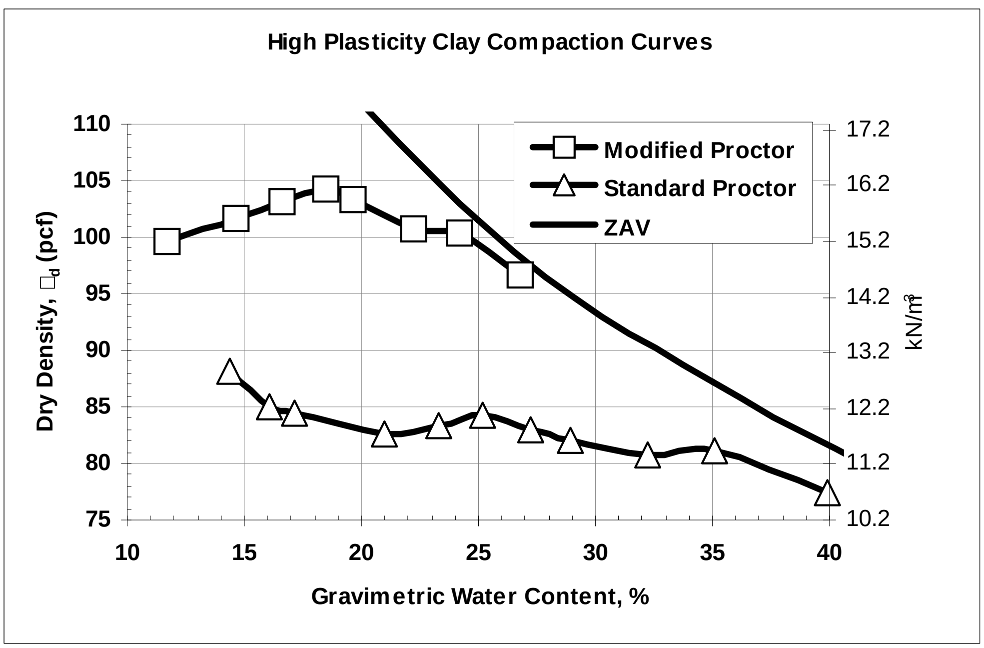

Figure 5. Atterberg Limits and Compaction Curves for High Plasticity Clay (CH) Material

DURA-BASE®

This matting system was originally designed and manufactured as a temporary load-bearing work platform system for use on low- and medium-strength soils by the oil-drilling industry. This matting system has proven to be durable under heavy truck and drilling equipment traffic over soft, low-strength soils. In addition, DURA-BASE® has been used by civilian airports for recovery of aircraft that have skidded off runways into perimeter, softer soils. These applications make this mat an ideal candidate for a JRAC application.

DURA-BASE® is a high-density polyethylene (HDPE) plastic mat, about 2.4 m (8 ft) by 4.25 m (14 ft) in surface area and 108 mm (4.25 in.) thick. A single panel weighs about 476 kg (1,050 lb) (about 9.4 psf) and provides an effective area of 2.1 m (7 ft) by 3.9 m (13 ft). The panels are connected by alignment of holes on the overlap and underlap edges of the mats. Each mat is composed of two identical sheets that are bolted together and heat welded with a designed off-set to achieve the overlap and underlap edges. The individual panels are held together with connector pins consisting of a metal pin encased in a plastic housing that fits in the oval connector pin holes manufactured in the mats. These connectors are turned a quarter turn to lock them in place and connect individual panels. An Allen-head wrench is provided by the manufacturer to lock the pins. DURA-BASE® is manufactured by Newpark Mats and Integrated Services based in Louisiana. Photo 8 shows the installation of DURA-BASE®. Photo 9 shows the connection pin assembly.

Photo 8. Dura-Base® Mat Being Assembled on Medium-Strength Subgrade Test Section (Note: the Yellow Rods are Used to Align the Mat Holes for Pin Connection)

Photo 9. Dura-Base® Mat connection pin (courtesy Newpark Mats and Integrated Services, Inc.)

Bravo® Mat

Bravo® Mat is the second generation of the prototype mat originally designated SP-12. This is a lightweight matting system developed by Newpark Mats and Integrated Services based in Louisiana, the manufacturer of DURA-BASE®, initially for application in a medium and light industrial-type application. It has been used as rapidly deployable foot-traffic flooring for tents and temporary shelters in both civilian and military applications. It has also seen limited use as a surface for lightweight traffic from pickups and carts. The mat is 1.22 m × 1.22 m (4.0 ft × 4.0 ft) with effective area dimensions of 1.08 m × 1.08 m (3.54 ft × 3.54 ft). The mat is 64 mm (2.5 in.) in thickness. Bravo® Mat can be manufactured in any color desired, including the standard colors of slate gray and desert tan. It weighs about 20 kg (45 lb) per panel (about 2.8 psf). Like DURA-BASE®, this system joins panels together using overlapping and underlapping edges. Unlike DURA-BASE®, this mat incorporates the connection pin, in this case manufactured completely of HDPE, in the mat itself. The pin requires a one-quarter turn with an Allen-head wrench (supplied by the manufacturer) in order to lock it in place (Photo 10).

ACE-Mat™

ACE-Mat™ was originally developed for expedient road construction over sandy soils by the ERDC. The product is currently licensed by the U.S. Government for manufacture by GFI, Inc. of Harrison, Arkansas. ACE-Mat™ has been found to be durable for application of heavy truck traffic over loose, sandy soils. In addition, they have been used to construct helipads in sandy soils and used to build aprons in silty-sand soils for C-130 aircraft (Anderton and Gartrell, 2005).

Photo 10. Turning the Pin in a Bravo® Mat to Lock It in Place

The ACE-Mat™ is a 5-ply fiberglass panel approximately 2.0 m × 2.0 m (6 ft-8 in. × 6 ft-8 in.) in overall area, producing a useable surface of 3.34 m^2 (36 ft^2) when connected. The mat is 9.5 mm (0.375 in.) thick. The panels weigh about 52 kg (115 lb) (about 2.6 psf) each and can be easily handled by two people. The panels are connected by locking aluminum pins. Each panel has underlap edges on two sides and corresponding overlap edges on the other two sides. The pins go through both panel lap edges, and when turned, the bottom half of the pin rotates 90 degrees and locks the panel edges together. When required, an ACE-Mat™ system can be held in place through the use of “duckbill” cable anchors (also known in industry as Manta-Ray anchors) (Photos 11 and 12) driven into the soil and connected to the outside edges of the panels. Photo 13 shows the assembly of ACE-Mat™ on the test section, with the

overlap/underlap pattern visible. Photo 14 shows a profile of the ACE-Mat™ connection pin assembly.

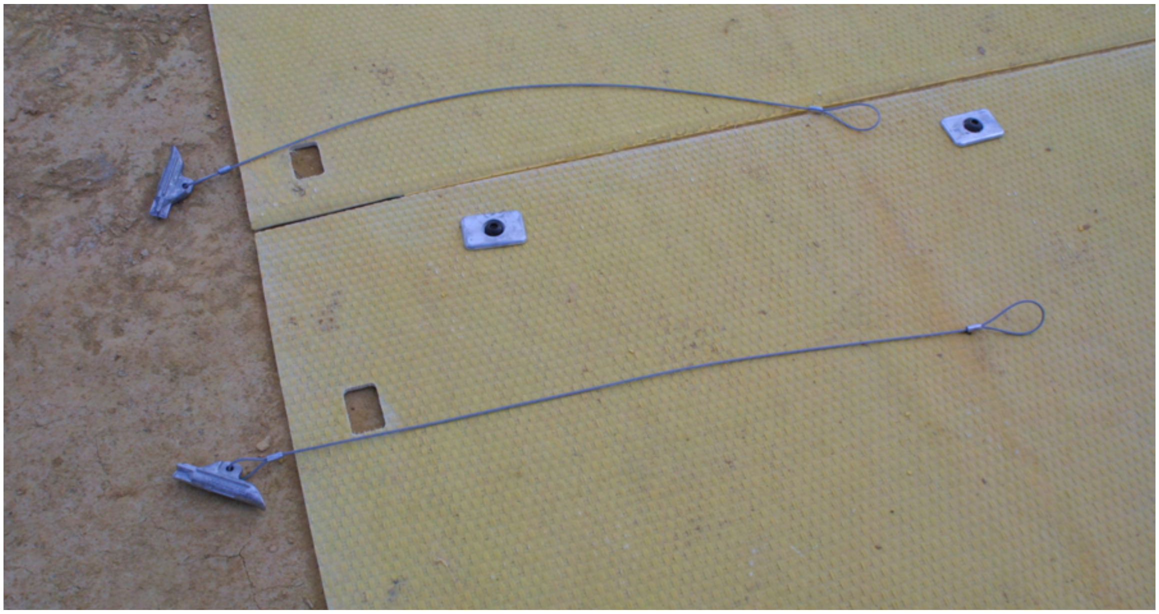

Photo 11. Duckbill Anchors Used to Secure ACE-Mat™ to the Ground

Design Considerations

The medium strength test section (8 to 10 CBR) was approximately 30.5 m (100 ft) long and 18.3 m (60 ft) wide with a depth of about 1.5 m (5 ft). These dimensions were utilized to accommodate the C-17 load cart, and to allow installation of various sized matting systems. Soil stress and strain sensors were installed in the section at various depths to record response and performance of the soil under load. These sensors will be discussed further in the "Instrumentation" section of this chapter. This data was collected for future use in the calibration and verification of modeling programs being developed for the testing of future matting systems as part of another work unit within the JRAC program.

Photo 12. Gasoline-Powered Hammer-Drill Being Used to Install Duckbill Anchor—
These Soldiers were involved in an Exercise Separate of JRAC

Photo 13. ACE-Mat™ on the Medium-Strength Subgrade Test Section (Note the underlap and overlap pattern of the mat edges)

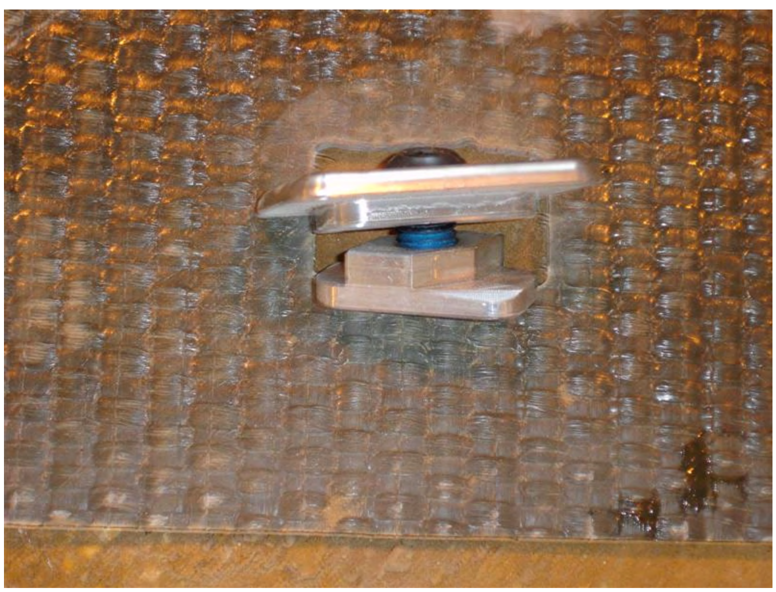

Photo 14. ACE-Mat™ connection pin profile view

This medium strength test section was trafficked first with DURA-BASE® mat installed, followed by Bravo® Mat, ACE-Mat™, and finally the section was trafficked with no matting to gather control data. Prior to the installation of each matting system and before the section with no mat (control) was trafficked, the section was pulverized and, if necessary, the top layer removed to allow the pulverization and wetting of the next layer below. These actions were required to return the section and its surface to its original moisture content, density, and CBR between test items.

Matting systems that successfully passed the medium-strength subgrade testing were applied to the low-strength subgrade (5 to 6 CBR) test section. The low strength test section had been originally constructed for use by the Rapid Parking Ramp Expansion (RPRE) program. This program was sponsored by the USAF to find a replacement for the AM2 matting system. This section was utilized by JRAC since RPRE was in an inactive period at the time of this testing. Because this section was previously in existence prior to its use by JRAC, and there was no time or resources available to reconstruct or modify the section, therefore, no instrumentation was installed here.

Construction

The first step in construction of the medium strength test section was to excavate the approximately 18.3 m (60 ft) wide and 30.5 m (100 ft) area to a depth of 1.5 m (5 ft). The section was built in 8-in. compacted lifts (a total of seven full and one partial lift). Moisture content and density to achieve the 8 to 10 CBR were 8 percent and 130 pcf, respectfully. Approximately 1,147 m^3 (1,500 cu yd) of this blend material were required to complete the test section.

Compaction was accomplished with a 22,679-kg (25-ton) pneumatic tired roller for initial compaction, with finish rolling performed using a 10,500-kg (23,150-lb) smooth steel drum vibratory roller with a dynamic force output of 16,329 kg (36 kips) at 2,400 rpm (Photo 15). Each lift was tested for moisture using gravity and nuclear test methods. Density was measured with a nuclear gauge. The dynamic cone penetrometer (DCP) was utilized once a backfill level of 610 mm (24 in.) was reached. This allowed sufficient depth of soil for the DCP to be effective. Table 4 shows engineering test data obtained during both medium and low strength section construction. Figure 6 gives the approximate locations of these tests, as well as layout, of the medium strength section. Figure 7 shows test locations and layout of the low strength section. The finished section surfaces were tested with a field CBR apparatus to determine the final surface CBR (Photo 16). As construction progressed and lifts were installed, the sensors were installed.

Photo 15. Installation of SM Blend in Test Section – Finish Compaction with the Vibratory Steel-Wheel Roller – Installation 50 percent Complete in this photo.

Table 4. Selected Pre- and Post-Traffic Soil Property Values

Test Item	**Medium Strength Soil (8-10 CBR)**						**Low Strength Soil (5-6 CBR)**			
	Pre-Traffic			Post-Traffic			Pre-Traffic		Post-Traffic	
	Test Pt. 1	Test Pt. 2	Test Pt. 3	Test Pt. 1	Test Pt. 2	Test Pt. 3	Test 1 Pt.	Test 2 Pt.	Test Pt. 1	Test Pt. 2
Control										
Field CBR	8	7	10.4	----	----	----	5.6	5.8	8.3	5.9
DCP CBR	12	8	8	7	8	10	6.5	6.5	7.8	6.5
Gravity Moisture (%)	6.5	6.4	6.8	5.6	6.2	6.7	28.7	28.7	27.8	29
Nuclear Moisture (%)	6.5	6.6	6.6	5.9	6.8	6.2	32.3	32.4	30.6	33.1
Microwave Moisture (%)	6.12	5.89	6.45	5.52	6.31	6.47	----	----	----	----
Wet Nuclear Density (pcf)	141.4	141.3	140.6	142.4	140.4	140.2	117.6	117.5	118.8	118.4
Dry Nuclear Density (pcf)	132.9	132.6	132	134.4	131.9	132.1	88.9	88.7	91	87.4
DuraBase										
Field CBR	----	12.8*	----	----	43.0**	----	6.3	6.4	11.5	11
DCP CBR	10	8	12	20	28	28	7	8	8	9
Gravity Moisture	8.58	7.88	7.48	7.2	6.08	5.84	31.5	31	32	30.5
Nuclear Moisture	8.2	7.8	6.9	7	6.4	5.3	31.4	32.5	27	27.3
Microwave Moisture	7.94	----	----	7.02	6.31	5.69	----	----	----	----
Wet Nuclear Density	139.5	139	135.8	139.6	140.3	137.2	118.5	118.7	120.8	119.2
Dry Nuclear Density	129.5	129.1	127.1	130.5	131.9	130.2	90.2	89.7	93.2	91.8
ACE Mat										
Field CBR	8.2***	8.2	----	----	----	----	6.2	5.9	7.4	7.3
DCP CBR	6	6	8	22	22	35	6.5	6	6	7
Gravity Moisture	6.5	6.6	6.8	6.2	6.9	7.6	32.7	32.1	33.5	33.8
Nuclear Moisture	6.9	6.8	6.9	7.2	6.6	6.4	32.1	30.6	32.9	29.2
Microwave Moisture	6.15	6.58	6.34	----	----	----	----	----	----	----
Wet Nuclear Density	138.3	138.4	140.7	141.1	142.2	140.8	118.5	117.2	116	116.2
Dry Nuclear Density	129.4	129.6	131.7	131.7	133.5	132.4	89.7	88.5	87.3	93.2
Bravo Mat										
Field CBR	11.2****	7.1	9.8***	----	----	----				
DCP	6	6	8	22	22	35				
Gravity Moisture	6.5	7.2	6.9	5.1	5.4	5	**BRAVO MAT FAILED ON MEDIUM**			
Nuclear Moisture	6.7	7.1	7.1	4.3	4.7	4	**STRENGTH SUBGRADE AND WAS NOT**			
Microwave Moisture	6.7	6.6	6.8	5	5.3	4.88	**TESTED ON LOW STRENGTH SUBGRADE**			
Wet Nuclear Density	139.1	139.9	139.1	138.8	139.2	136.7				
Dry Nuclear Density	130.5	130.7	129.9	133.1	133	131.4				

Notes:

1. "----" indicates that no data was recorded at this station.
2. **Field CBR values were used as the standard for soil strength in this project.**
3. DCP CBR values were taken from DCP CBR data plots, using the CBR value estimated at a depth of 5 inches.
4. Field CBR values were taken from CBR data worksheets. Three CBR analyses were performed at each test point, with the final value being an average.
5. Three Nuclear Density Tests at one station were averaged to arrive at the final values.

* Station. 65 - 15' East of Centerline
** Station. 35 - Centerline of Section
*** Station 20 - East of Centerline
**** Station 35 - West of Centerline

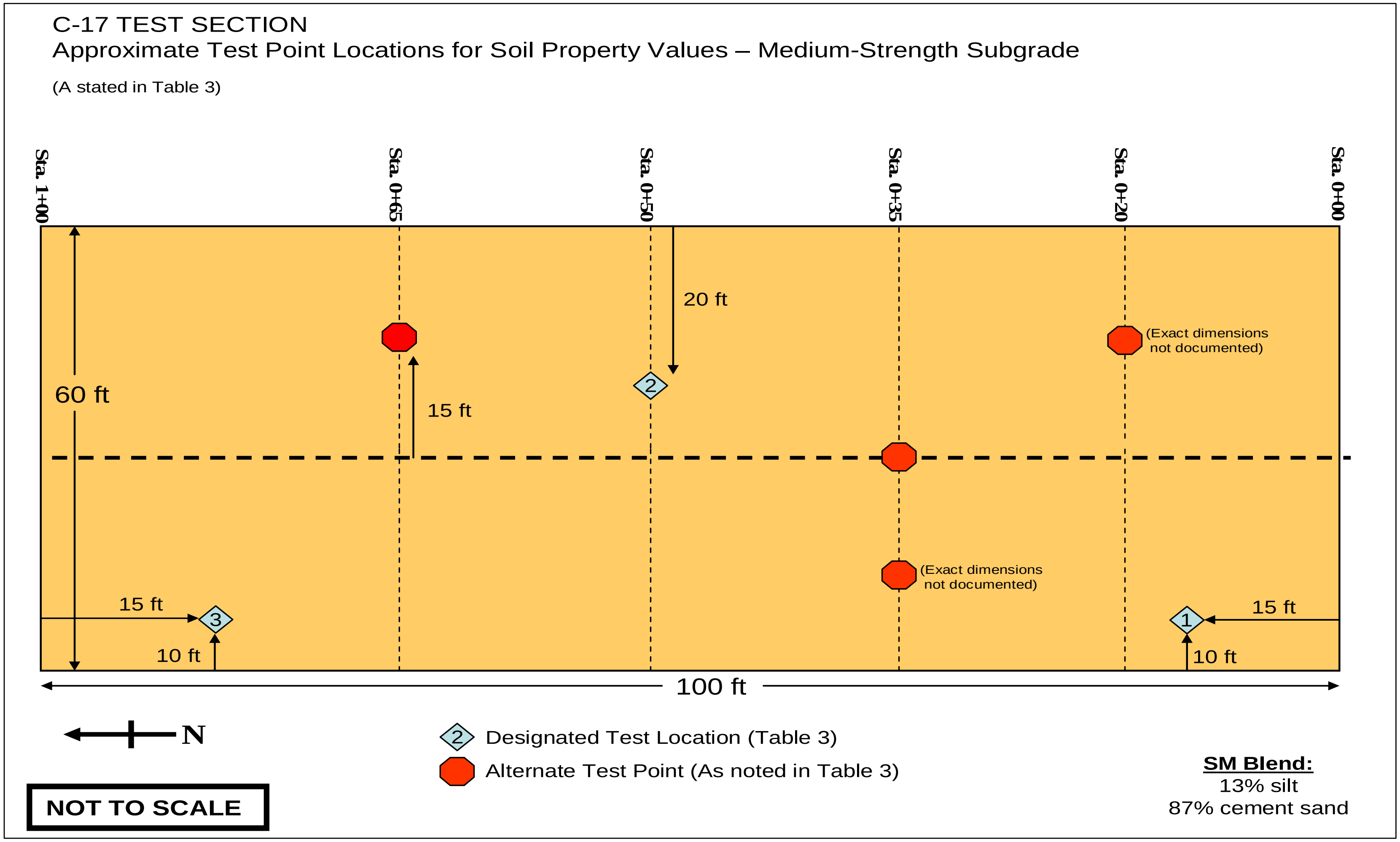

Figure 6. Test Point Locations and Test Section Layout – Medium-Strength Test Section

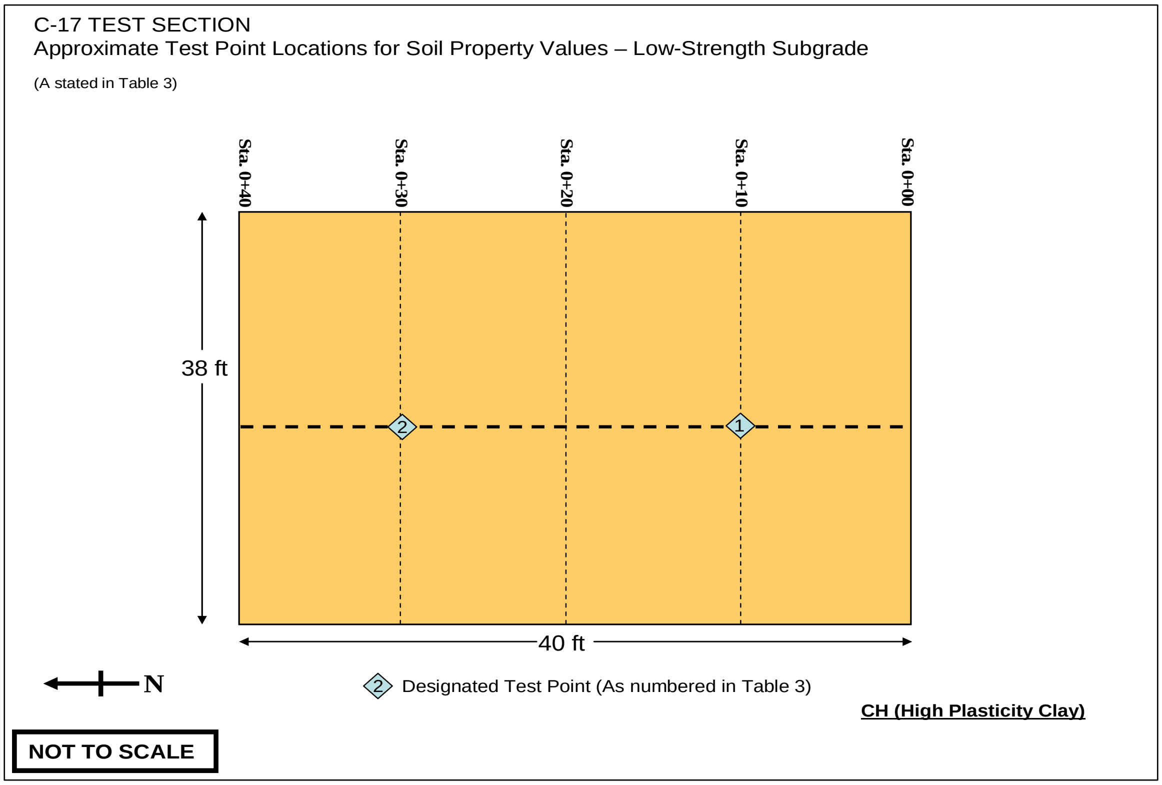

Figure 7. Test Point Locations and Test Section Layout – Low-Strength Test Section

With conclusion of the medium-strength section testing, the focus shifted to the low-strength (CBR 5 to 6) section testing. This was performed on the pre-existing clay (CH) section that had been used in the first MOG testing (C-130 aircraft) and most recently by the USAF for the RPRE program. The section measured 11.5 m (38 ft) wide by 12.1 m (40 ft) long and consisted of 610 mm (24 in.) of sand (CBR < 10) overlaid with 914 mm (36 in.) of CH material (CBR approximately 6). When it was originally constructed, the CH layer was lined on all sides and the bottom with a high-density polyethylene barrier to aid in the retention of moisture and maintenance of the target CBR. Figure 7 shows a general layout of the section.

Photo 16. Typical Field CBR Setup on the Finished SM Blend Test Section Surface

As discussed earlier, this section, built for testing in the RPRE Program, had been inactive for several months, loosing moisture and gaining stiffness. In order to utilize this section for the JRAC work, the first two layers of material 152 to 203 mm (about 6 to 8 in.) per layer were removed, the exposed surface was pulverized with a soil mixer, and water was applied to achieve the required moisture content for the specified CBR of 6. The two layers of material removed were hauled to a concrete pad for processing. The clay was reconditioned by pulverizing, adding water, and mixing until the proper moisture content for the desired strength was achieved. This moisture level was determined to be approximately 30 percent to achieve a final in-place 5 to 6 CBR. This moisture level is based on laboratory-generated Proctor (moisture-density) curves, as well as previous experience. The processed material was hauled by dump truck to Hangar 4

and spread with a bulldozer in 152-mm (6-in.) compacted lifts. Six-inch lift size was chosen to reduce problems associated with the workability and control of this material.

Density for the low strength section was about 88 pcf. This compaction required a moisture content of about 30 percent. Compaction was achieved by first using a 22,679-kg (25-ton) pneumatic tired roller for initial compaction, with finish rolling performed using a 10,500-kg (23,150-lb) smooth steel drum vibratory roller with a dynamic force output of 16,329 kg (36 kips) at 2,400 rpm. Table 4 lists engineering data obtained during construction of the section. Figure 7 gives approximate locations of the construction testing. As stated in "Design Considerations" of this chapter, this test section was pre-existing and some tests performed on the silty-sand section were not performed on the CH section. Photo 17 shows the CH test section prior to the application of DURA-BASE®.

Throughout construction of both the medium and low strength test sections, moisture control was an important key in achieving the target CBR. During construction, as well as during trafficking, the test section was covered at the end of each day and during any down time with a plastic sheeting to prevent excessive moisture loss. It was assumed the section would dry out during the testing, however the data showed the moisture loss was minimal.

Prior to applying traffic on the control item (no matting used) or any of the matting systems, test section surface cross sections were measured using a standard survey rod and level. See Figures 6 and 7 for the stationing of each test section. Subsequently, the matting systems were assembled according to the vendor's instructions. Cross sections on the matting system surface were also measured. Striping

was then applied to the matting surface (subgrade surface in the case of the control testing) to provide the load cart driver references for cart line-up and trafficking. Photo 18 shows the final surface of the silty-sand control test section prior to the start of traffic. Photo 19 shows the Bravo® mat prior to start of traffic.

Photo 17. CH Material Test Section Prior to Installation of DURA-BASE® Mat

All matting systems were weighted along both sides using lead blocks. Each block weighs approximately 907 kg (2,000 lb) and was spaced at 1.2 to 1.8 m (4 ft to 6 ft) intervals (Photo 20). The lead blocks were placed to anchor the sections, providing a simulation of wider, full scale applications.

Photo 18. Control Test Section – SM Blend – Stripped and Ready for Traffic

Photo 19. Bravo® Matting Striped and Ready for Traffic – Lead Weights on Sides Used as Edge Anchors

Photo 20. Placement of 907-kg (2,000-lb) Lead Weight on Edge of ACE-Mat™

After trafficking, the matting system was removed and the final surface cross sections, as well as other data, were collected. The test section was reconstituted with a soil mixing machine, adjusting water content if needed, and the material recompacted until the required CBR value range (8 to 10 for the medium strength section or 5 to 6 for the low strength section) was achieved. For the silty sand test section, extra care was taken to protect and preserve instrumentation during the reconstitution process. If during the reconstitution process, it was determined that the layer below the surface layer was consolidated from trafficking, then after mixing of the top layer, this layer was removed to allow mixing and moisture adjustment of the second layer. The need to reconstitute the

third layer from the surface was never encountered. This process continued for all of the matting system and control section testing performed.

Instrumentation

Initially, the Rapid MOG Enhancement project did not include instrumentation or sensors. The reason is most of the criteria for this project involved mat damage and deformation during traffic, and the use of instrumentation was not required. However, several others work units within JRAC involved development of finite element models to simulate airfield stabilization methods. This thesis also makes use of some of the data from the medium strength test section to perform analyses of the mats tested for the C-17 aircraft. That effort is documented in the next chapter. Dr. Ernest Berney, a research leader within the JRAC program, examined use of finite element analysis of airfield mats and other materials within JRAC. Dr. Berney devised the instrumentation layout and protocol for the silty sand test section. As stated earlier, the CH material test section did not employ instrumentation.

Three types of instruments, or sensors, were installed in the silty sand test section: pressure cells, single depth deflectometers, and compaction gauges. Pressure cells were installed in two configurations, horizontal and vertical, to capture pressures in these two orientations. The following paragraphs describe instruments installed and their purpose.

Geokon Model 3500

In application, the pressure cells are sensors that measure total earth pressure. The cells consist of two 229-mm (9-in.) diameter plates that encapsulate a thin layer of fluid. When the pressure is applied to the plates the fluid pressure is captured by a transducer.

The voltage output of the pressure transducer is converted to a pressure and recorded by the computer. Photo 21 shows a Geokon Model 3500 being installed in the medium strength test section. The medium strength section used two ranges of the Geokon cell. The high range version was capable of pressures up to about 620 kPa (90 psi). The low range version was capable of pressures up to about 96 kPa (14 psi).

Photo 21. Geokon Model 3500 Pressure Cell Being Installed in the Medium Strength Test Section

Single Depth Deflectometer

Single depth deflectometers (SDDs) used in this study measured deflection under load at a particular location and elevation in the test section. SDDs are actually a combination of several components: the transducer (linear variable differential transformer or LVDT), the transducer housing, the layer plate, and the anchor. To install

this sensor, a hole is bored vertically in the test section to a depth below the area of influence of the loads that will be applied. The anchor is grouted in place at this depth below the area of influence with a general cement grout mixture that flows easily. Next, the transducer housing and plate are installed. The transducer, or LVDT is then placed in the housing and calibrated. During the adjustment the LVDT comes into contact with the anchor rod. Once the adjustments are completed, the LVDT is covered with a plate that fits the housing opening. When the plate and housing move with the surrounding soil layer, the LVDT moves with the housing and the displacement is measured in reference to the fixed anchor rod. Single depth deflectometers (SDD) allow the user to monitor the soil deflection at a single depth as the load is applied. The LVDT's used here were spring loaded, so both elastic and plastic deformation can be observed. The housings, plates and anchors of the SDD assemblies used here were fabricated at the ERDC machine shop facilities. The Photo 22 shows the transducer used in the SDD device.

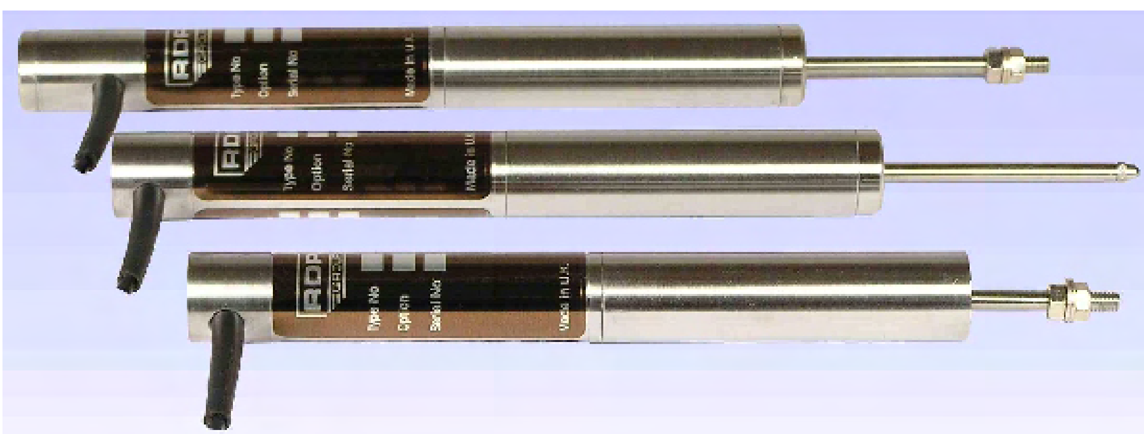

Photo 22. RDP Group LDC Series LVDT Displacement Transducer

CTL Group Compression Gauges

Compression gauges are used to measure compression of the soil at a particular depth of the pavement structure when a load is applied. Photo 23 shows the sensor as it is supplied before installation. A sensor between the two plates measures the displacement of the plates and translates this into a voltage that is sent back to the monitoring computer for display and/or recording. The resulting data is percent strain. Unlike the SDDs, this instrument does not have a spring to return it to normal length if the deformation is elastic. This device records plastic, or permanent, compression in the soil. The initial distance between the two plates is 152 mm (6 in.).

Photo 23. Soil Compression Gauge by CTL Group

In the instrumentation layouts that follow several sensors appear under the ACE-Mat™ and Bravo® mat that were not present under the DURA-BASE®. Additional sensors were installed in the section after DURA-BASE® testing to enhance data collection. All of the sensors installed are sensitive, and can be easily damaged during testing. As a result, several failed prior to completion of the testing. The presence of multiple sensors prevented data loss.

Figures 8 through 10 show approximate instrumentation locations in relation to the individual matting systems trafficked on the silty sand test section. As illustrated, some sensors were placed on the joints, while others were placed in the center or near the edge of the matting systems. Figure 11 graphically depicts the location of the sensors in the profile view, giving depth and location. The sensors were installed during initial construction of the section itself and remained in place throughout the test section work. Several sensors were unearthed during reconstitution of the test section for maintenance and/or repair, but were reinstalled in the section in the same locations.

An in-depth analysis of these data will not be performed in this thesis, but several example plots of the data collected are presented in Figures 12 and 13. These figures map out small segments of time where the load cart is being driven across the section. The graphs show two very steep peaks, which are the front and rear tires of the C-17 main gear as it rolls across the test section. The landing gear configuration of the C-17 is illustrated in Figure 14. Although not as easily seen in all the plots, a third peak is also present, though not as dramatic, that represents the tire of the tractor (Photo 24) that is pulling the cart across the section. Some specific points of the instrumentation data will be used in the following modeling efforts.

A comparison of the pass levels and plotted response shows an increase in pressures recorded at 1001 passes on the DURA-BASE®. In contrast, the pressure decreases at 1001 passes on the ACE-Mat™. This would seem contradictory to what is expected, however, there are several possible explanations. As traffic progressed, and the soil was shifted beneath the mats, the sensors could have been moved, causing inaccuracies in the measured data. Soil collapse or bridging could have taken place on a very small scale,

again, causing erroneous measurement. However, the most likely cause was shifting of the traffic pattern. The exact location of the sensors was not marked for traffic. In addition, traffic with such a large load cart can be difficult to control when a shift of several inches can make a large difference in the location of the “cone of load influence” under the tire. By simply shifting the cart 152 mm (6 in.) from where it was suppose to roll, the pressure recorded by a sensor can vary by 69 to 138 kPa (10 to 20 psi). For the modeling effort that follows, initial response, or the first few passes, was the only information needed. These variations just discussed have no effect on the modeling data utilized.

Trafficking and Data Collection

The medium and low strength test sections evaluated the effects of a full, contingency loaded (loading rates for aircraft operations on semi-prepared, or dirt, surfaces) C-17 aircraft on the tested matting systems. The load cart for applying traffic consisted of a FIAT brand, two-wheel tractor connected to a custom-design and built trailer fitted with an exact 6-wheel bogie, fitted with actual C-17 aircraft tires, that mocks one main gear set of the C-17 aircraft (Photo 24). The cart was loaded with lead blocks to a total weight of 93,267 kg (15,544 kg per tire) [205,620 lb (34,270 lb per tire)], which is the amount of weight on each main gear for contingency level loading of the aircraft, based on U.S. Air Force criteria (ETL 97-9). The tires were each inflated to 965 kPa (140 psi).

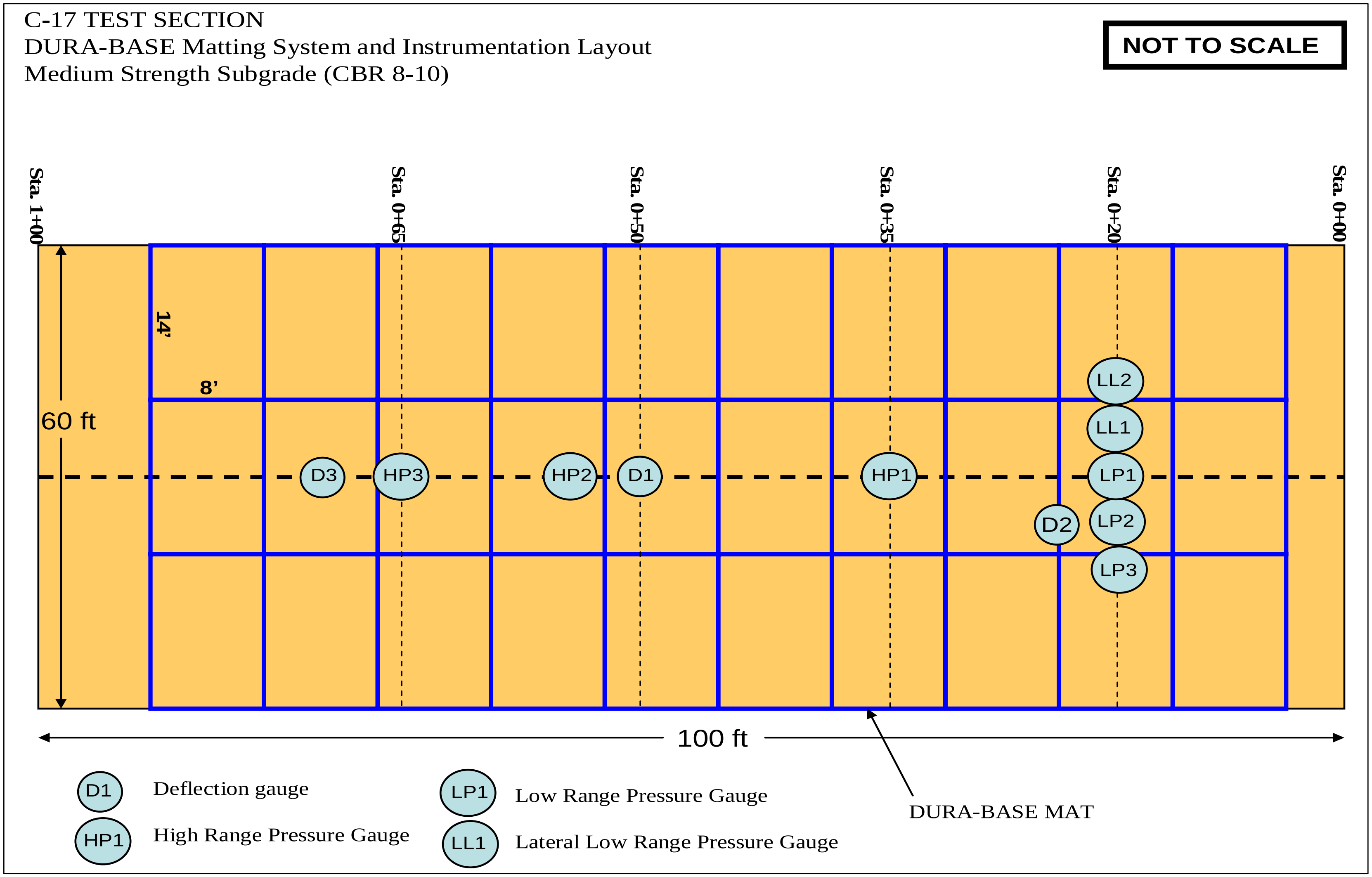

Figure 8. Test Section/Instrumentation Layout – DURA-BASE® Mat System – Silty Sand Test Section

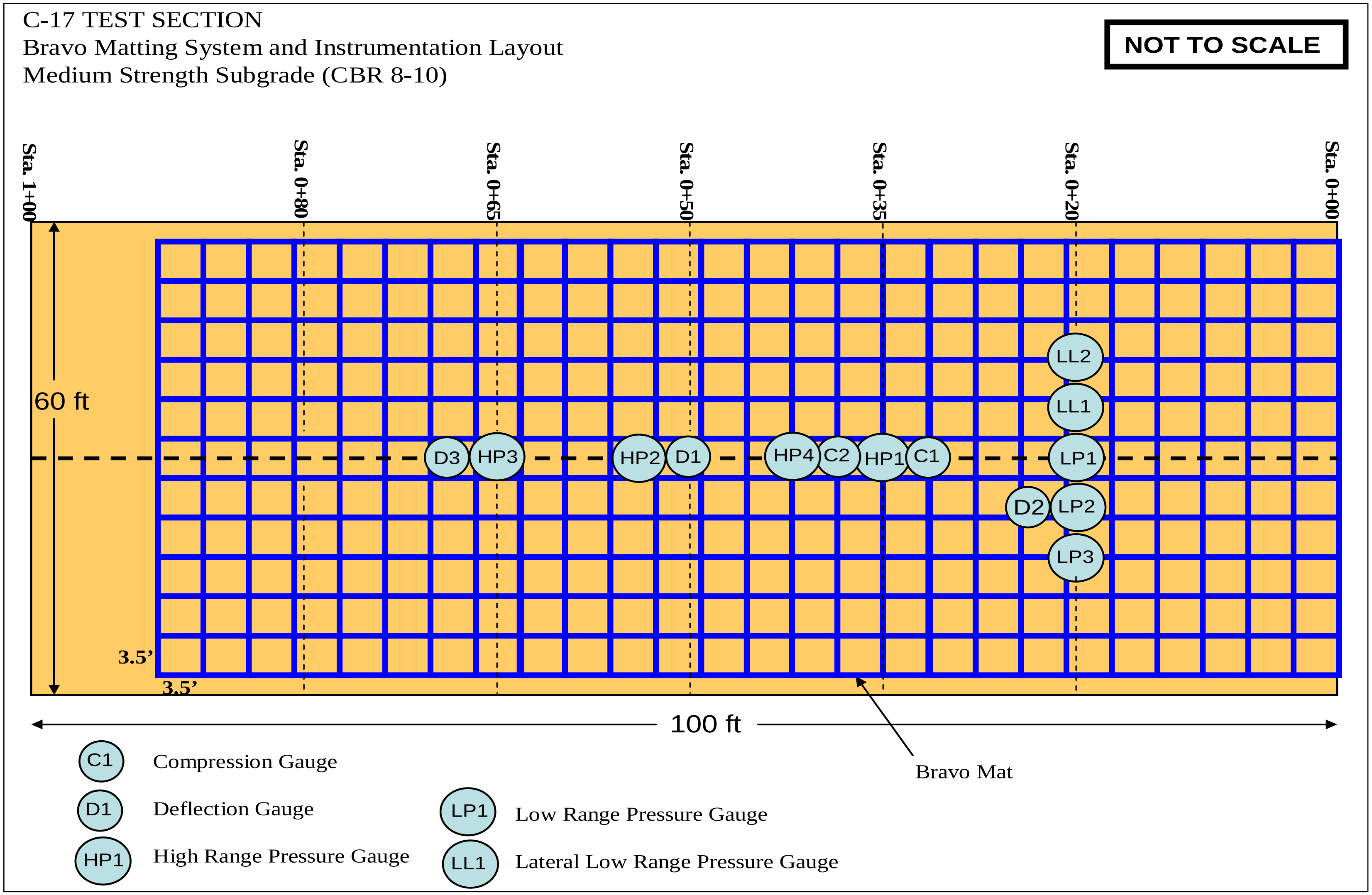

Figure 9. Test Section/Instrumentation Layout – Bravo® Mat System – Silty Sand Test Section

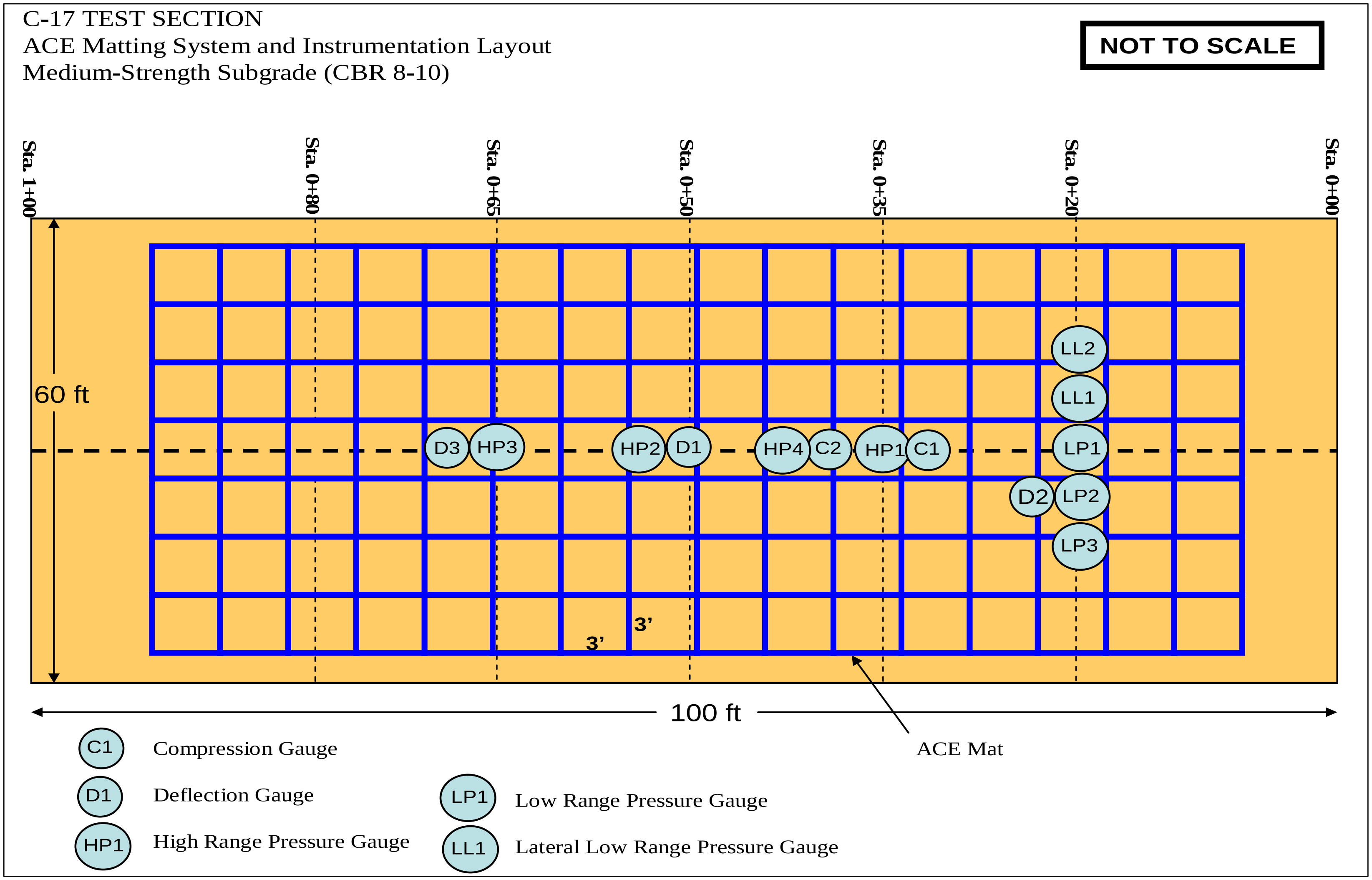

Figure 10. Test Section/Instrumentation Layout – ACE-Mat™ System – Silty Sand Test Section

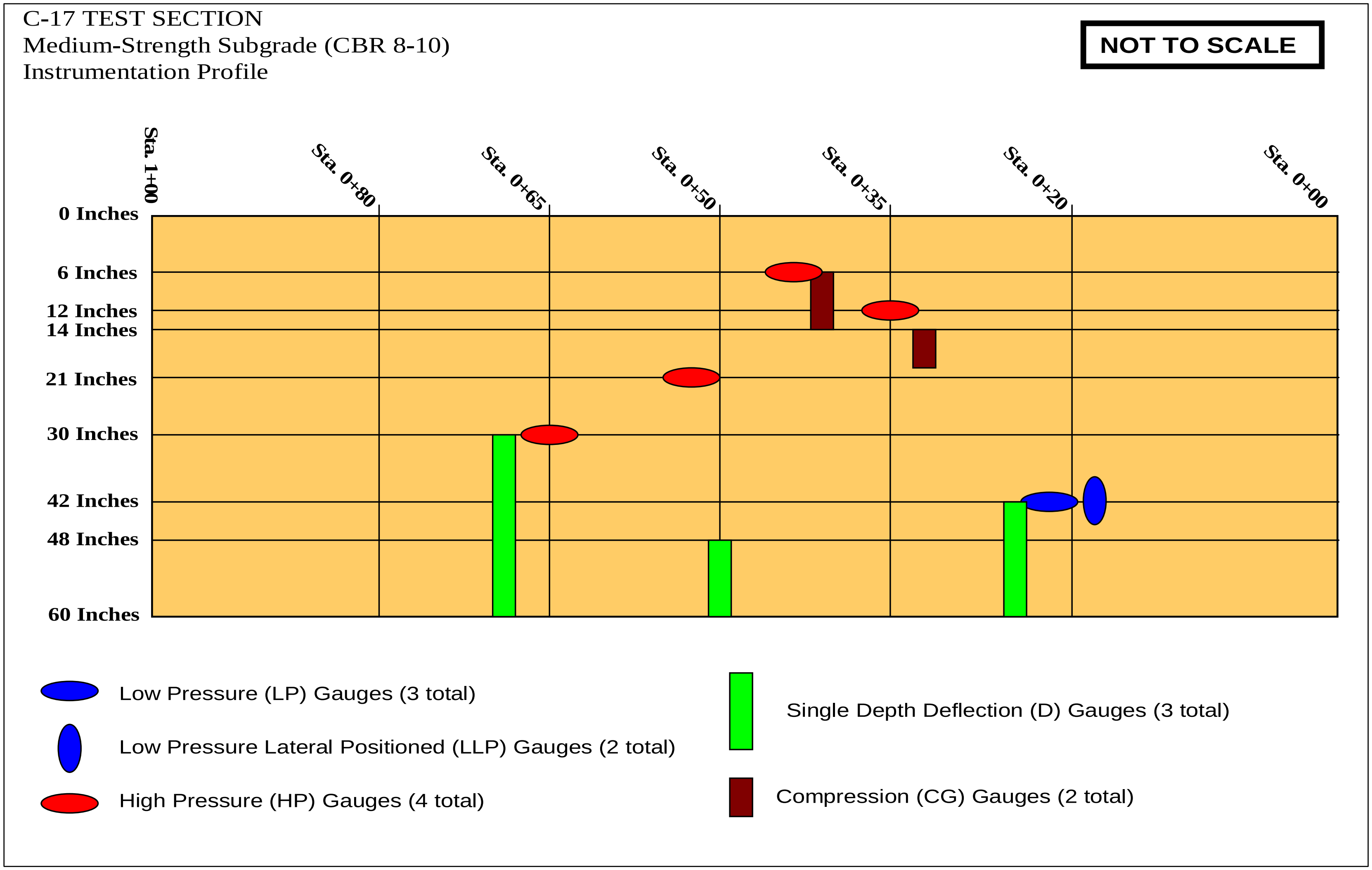

Figure 11. Test Section/Instrumentation Profile – Silty Sand Test Section

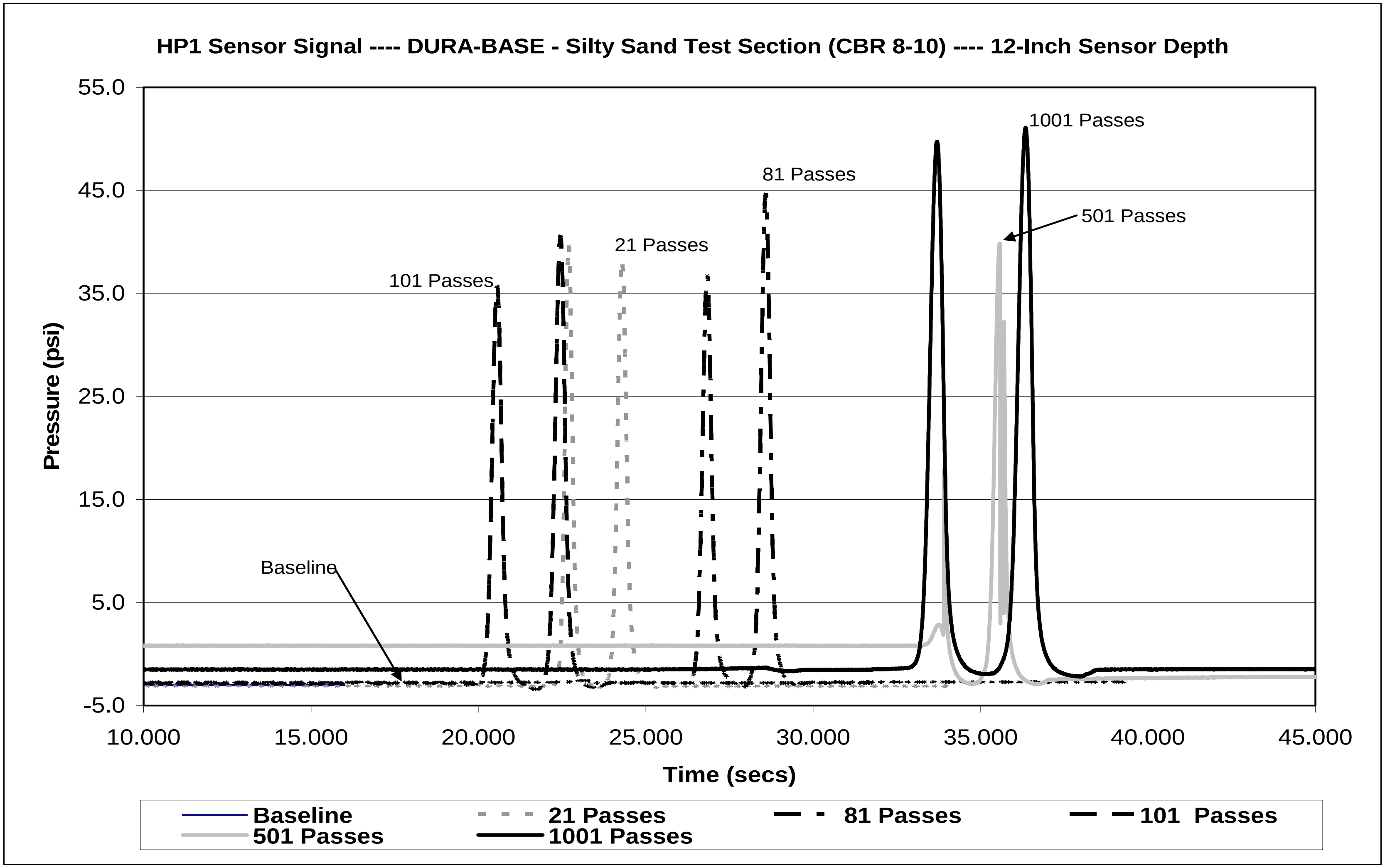

Figure 12. HP1 Earth Pressure Cell Signal Data – DURA-BASE® – Silty Sand Test Section

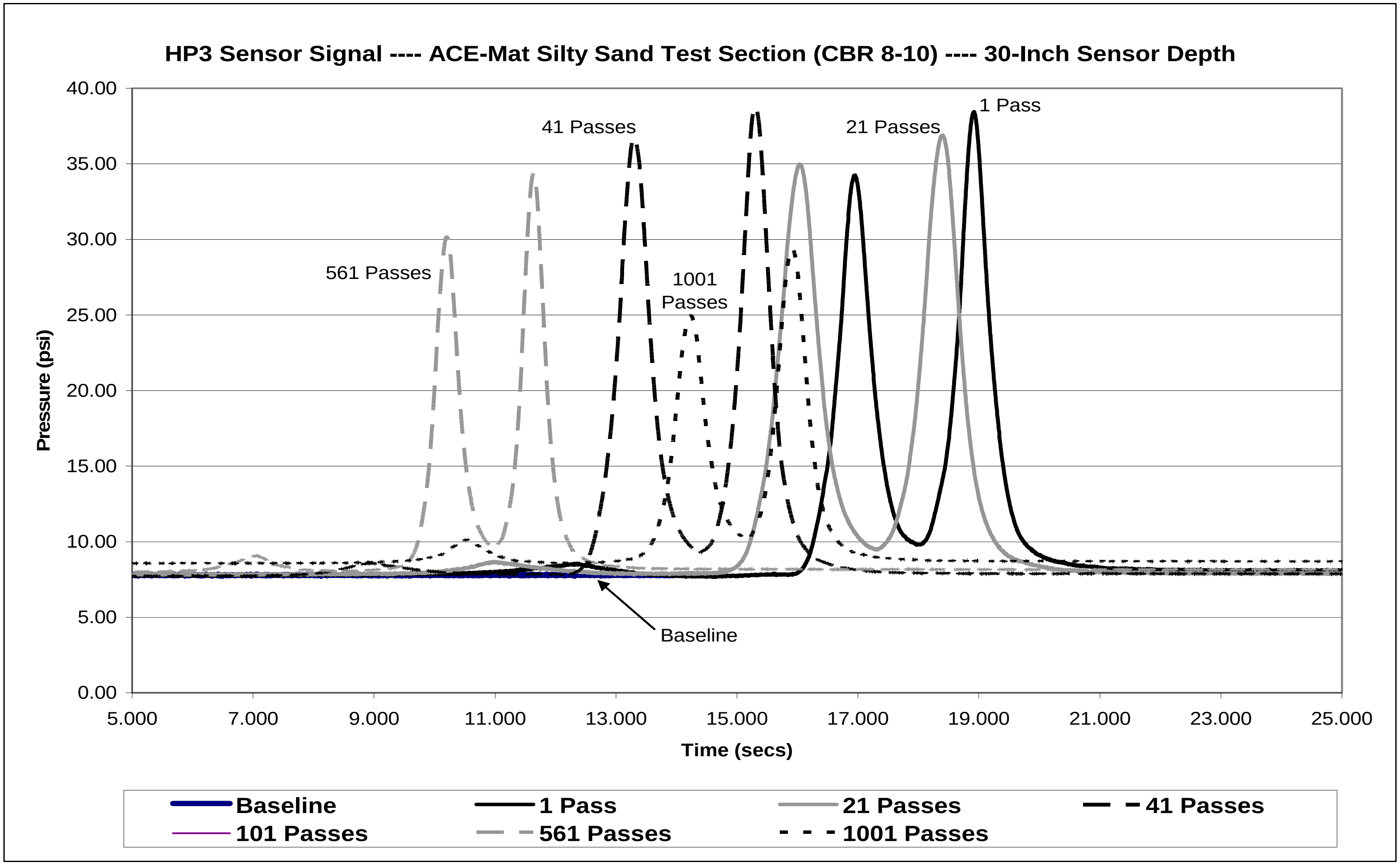

Figure 13. HP3 Earth Pressure Cell Signal Data – ACE-Mat™ -- Silty Sand Test Section

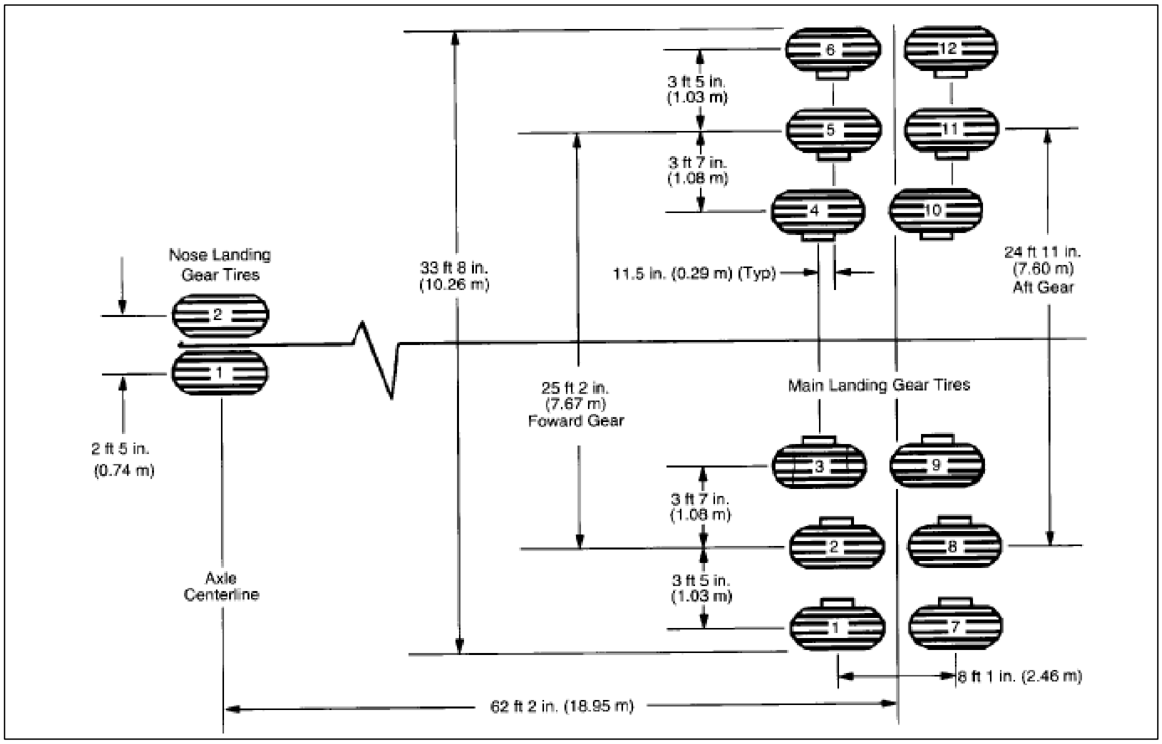

Figure 14. C-17 Landing Gear Configuration (After Air Force Civil Engineering Support Agency, ETL 97-9, 1997)

Photo 24. C-17 Load Cart (C-17 Mock Gear Set is Behind Large Outrigger Tire)

Traffic was applied in a normalized distribution pattern representing theoretical wander of the aircraft. The following definitions will aid in understanding the application of traffic:

- Pass: one traverse of the load cart across a given length of runway, taxiway or test section surface,
- Coverage the application of the wheel of an aircraft or test load vehicle over a single point on a runway, taxiway, apron, or test section,
- Pattern is defined as the completion of one simulated normal distribution of traffic across a test section.

The traffic pattern used in this work is shown in Figure 15. With this pattern, 20 passes of the cart were required to produce one complete pattern over the section.

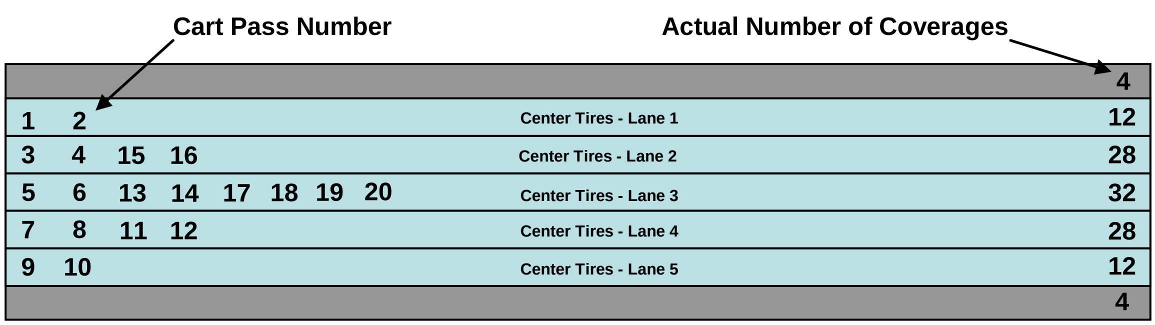

Figure 15. C-17 6-Wheel Load Cart Traffic Pattern

The traffic pattern in Figure 15 shows the pass numbers for each lane, and the lanes shown are for the center tires of the landing gear configuration only. So in reality, each lane will get multiple coverages by different tires of the gear, as shown by the actual number of coverages on the right side of the figure. For test and data measurement purposes, only the path and passes of the center tires are considered. A layout of the entire C-17 gear configuration is shown in Figure 14. The load cart used in this project simulates one of the main gears of the aircraft.

Graphically, the actual coverages received by each lane are shown in Figure 16. This figure illustrates the position of each lane, coverages of each lane, and the normal curve of coverage that is achieved.

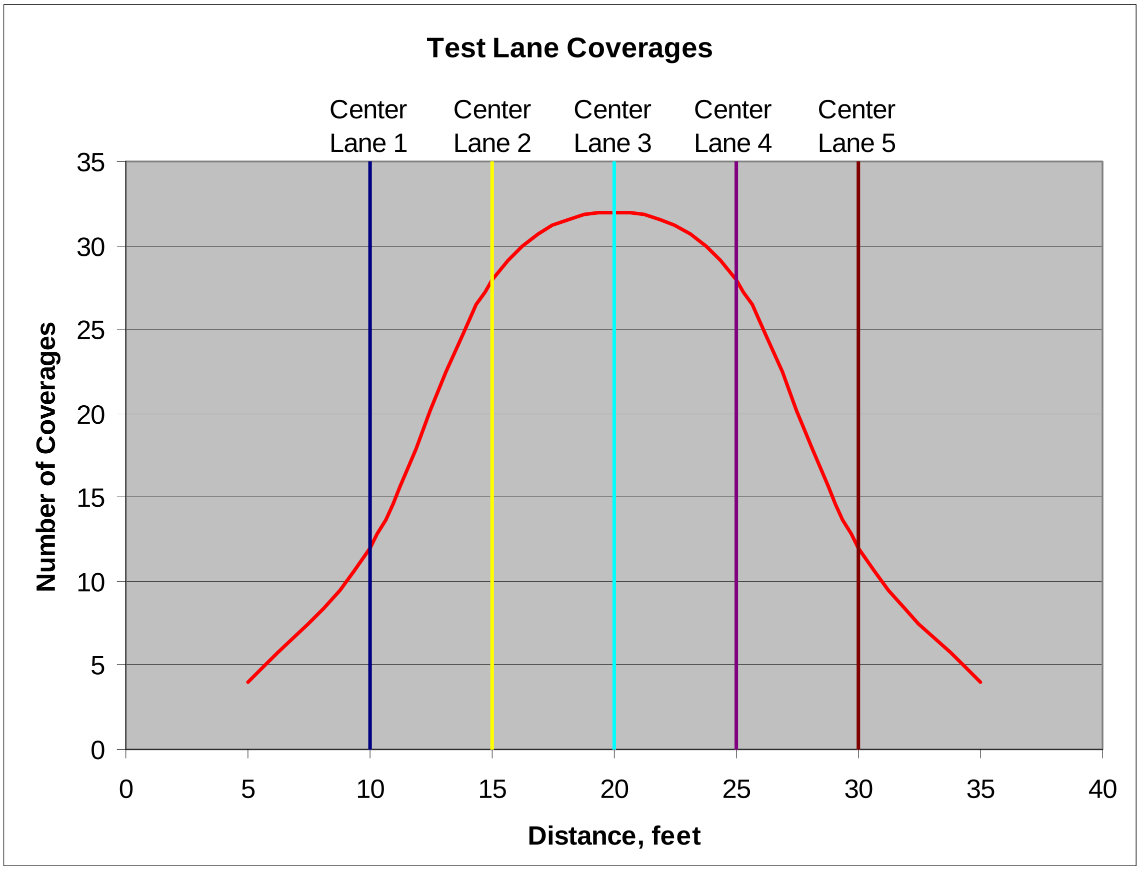

Figure 16. Coverages and Modified Normal Distribution of C-17 Load Cart Traffic

Data collection intervals varied. For cross sections, rut (deformation) measurements, and mat damage assessment, the test plan called for center lane pass levels as follows: 0, 20, 40, 60, 80, 100, 120, 160, 200, 240, 280, 320, 360, 400, 480, 560, 720, and 1000. These intervals were modified when required, based on damage observed, visual indication of major changes in the rut (deformation), or noticeable trends

in the data recorded to that point. Instrumentation sensor data collection was performed at predetermined center lane pass levels as follows: 8, 16, 20, 22, 28, 36, 40, 42, 48, 56, 60, 62, 68, 76, 80, 82, 88, 96, 100, and 102. These levels were chosen to insure that the load cart was moving forward on the test section and was traveling along the center lane of the section. It was determined that these various levels would insure that adequate data was available for calibration of developing finite element analysis (FEA) models, as briefly discussed earlier.

All surface cross sections and profiles were recorded using a standard surveyor's rod and level. Cross sections were taken along the designated stations (see Figures 8, 9, and 10) except at Stations 0+00 and 1+00. Profiles were measured along the centerline of the test section. A permanent benchmark located in Hangar 4 was used to establish and maintain elevation control. Baseline data were recorded prior to the placement of the matting system, after placement of the matting system and prior to traffic, and final cross sections and rut measurements were taken after the matting system had failed and was removed from the test section. During trafficking, cross sections and rut depth measurements were taken, initially based on the pass levels described above. Any observable mat damage was also examined and noted at these same intervals. The failure criteria for this project are presented in the next section.

A 3.04 m (10 ft) aluminum straight edge was used to obtain measurements of total rut depth. Rut was defined here as the distance from the highest elevation to the lowest elevation in the wheel path. As the rut began to form in the section, the rut bar was placed along each cross section line (perpendicular to traffic) with a ruler used to measure distance from the bottom edge of the bar to the mat surface. The largest distance

measured along the bar at that cross section line was considered the rut depth for that station at that pass level.

During trafficking, a front-end loader, with the bucket full of sand, was used to compress the mat surface to allow the measurement of rutting (Photo 25). On the DURA-BASE® matting system, this was especially critical, as this system has a high stiffness value and is very resilient. Without this counterweight in place, mats can bridge the rut present in the soil underneath the mat section, preventing a measure of the rut that would be observed with the load cart on the mat. It is understood that the end loader will only deform the mat and allow the measure of the plastic deformation present under the mat. Elastic deformation, and therefore total deformation, can only be measured with the load cart in place. Plastic deformation is not recovered, and it is this deformation that is used to determine if the matting system is given a “go” or “no go” rating. Additionally, the extreme weight of the load cart and the high pressure of the gear set tires results in extreme safety hazards for test section personnel working close to the tires when measuring deflections with the load cart in place.

Failure Criteria

Failure was defined as when the deformation or rut depth (crest to trough of rut, measured on the mat) reached a value of 76.2 mm (3 in.) or greater or a minimum of 20 percent of the mat system installed on the test section experienced severe damage (pin breakage, pin failure, cracks or breakage). The deformation of the mat and underlying soil was measured with the mat in place, using the rod and level and the rut bar, as described earlier. The mats were not removed from the subgrade until the failure

condition was reached. Photo 26 shows the measurement of the final rut depth after the removal of the matting system from the test section surface. The target for all mats tested was at least 1,000 passes with less than 76.2 mm (3 in.) of total rut with the mat in place over the soil. This was a change from the original testing criteria used with the C-130. In that testing, a minimum pass level of 2,000 was required. It was anticipated that under the C-17 loading, the best performance from the mats would be 1,000 passes without failure. It was also assumed that under the low-strength subgrade conditions (5 to 6 CBR) that failure would probably occur before the pass level of 1,000 was obtained.

Test Section Results

General Summary

Results of the mat testing indicate that in general, as the strength of the soil decreases, the capacity of that soil to support the load of the C-17 aircraft decreases as well. This result was expected. The purpose in this work was to quantify the ability of the matting systems to mitigate this loss of support capacity.

All of the desired data was collected and summarized for the silty sand (SM) test section and the high plasticity clay (CH) test section. Conclusions for the SM and CH sections are summarized below. Figures 17 and 18 illustrate the deformation or rut depth versus passes for the applicable matting systems.

Photo 25. Using Loaded Front-End Loader to Load the Mat for a True Deformation (Rut) Measure

Photo 26. Measuring the Permanent Deformation (Rut) on the CH After the Removal of the DURA-BASE®

Control

During each phase of testing, a control section was included to compare rutting of the soil with no matting systems to that with matting systems. With the SM test section (CBR 8 to 10), failure by deformation [rutting, ≥ 76.2-mm (3-in.)] occurred at 49 passes. Failure of the silty sand test section is shown in Photo 27. Failure due to deformation on the CH test section was achieved after only one pass. Photo 28 shows this section after failure.

DURA-BASE®

The DURA-BASE® matting system performed well throughout the test section evaluations on both the SM and CH sections. With the SM material, this mat exhibited 2.5 cm (1 in.) of deformation after 1001 passes of the load cart. The trend line plotted in Figure 17 indicates this mat could withstand as many as 10,000+ passes before reaching failure. This system is considered an excellent choice to increase the traffic capacity of medium-strength (CBR 8 to 10) soils subjected to the C-17 contingency loading. It is important to note that even with the performance of this mat, its weight, logistical footprint, and the need to have forklifts or similar equipment for handling will likely preclude its use in many cases. Photos 29 and 26 show the DURA-BASE® on the SM test section during traffic and rut measurement after removal of the DURA-BASE® on the CH test section, respectively.

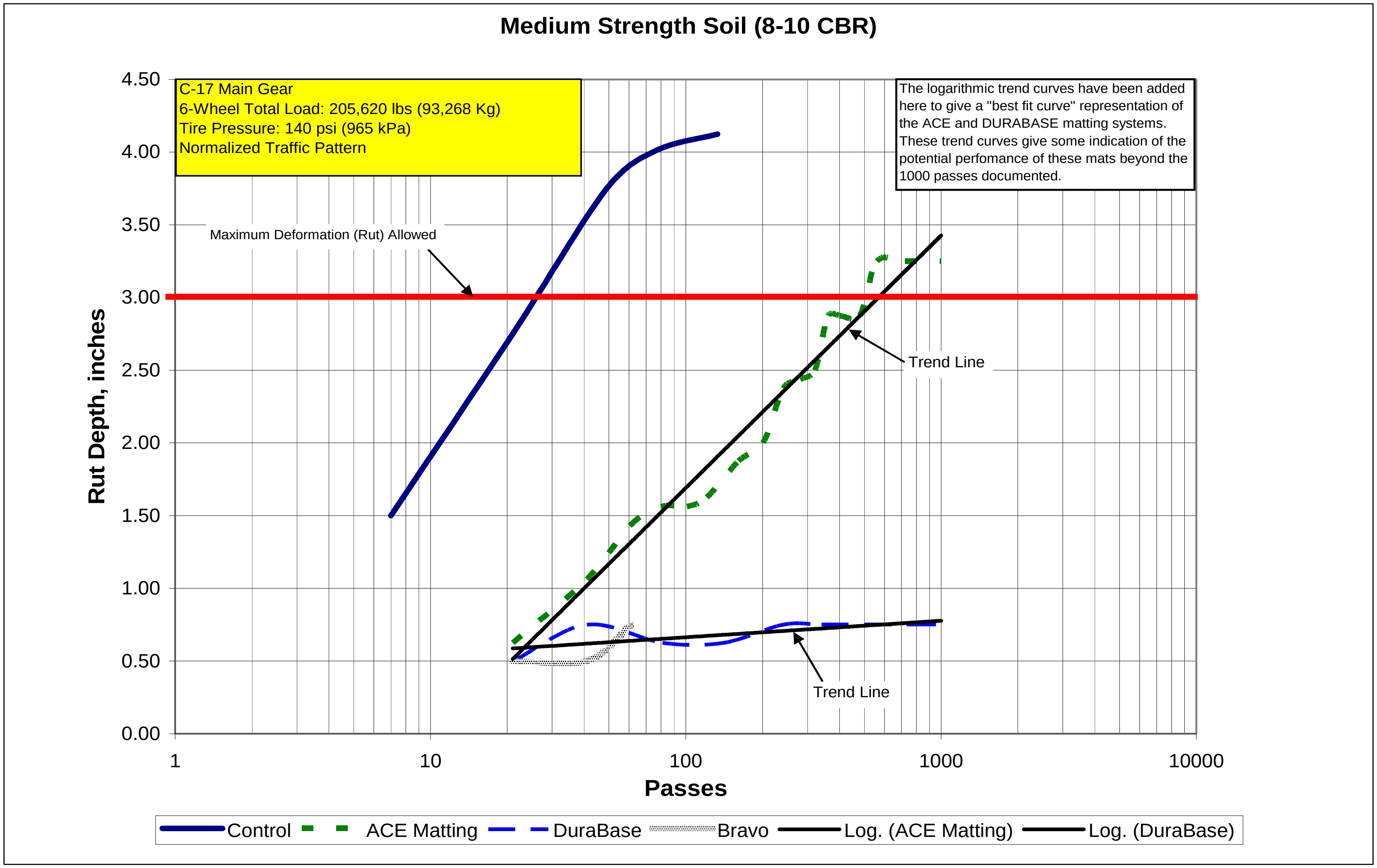

Figure 17. Deformation (Rut Depth) of Matting Systems on SM Soil Test Section

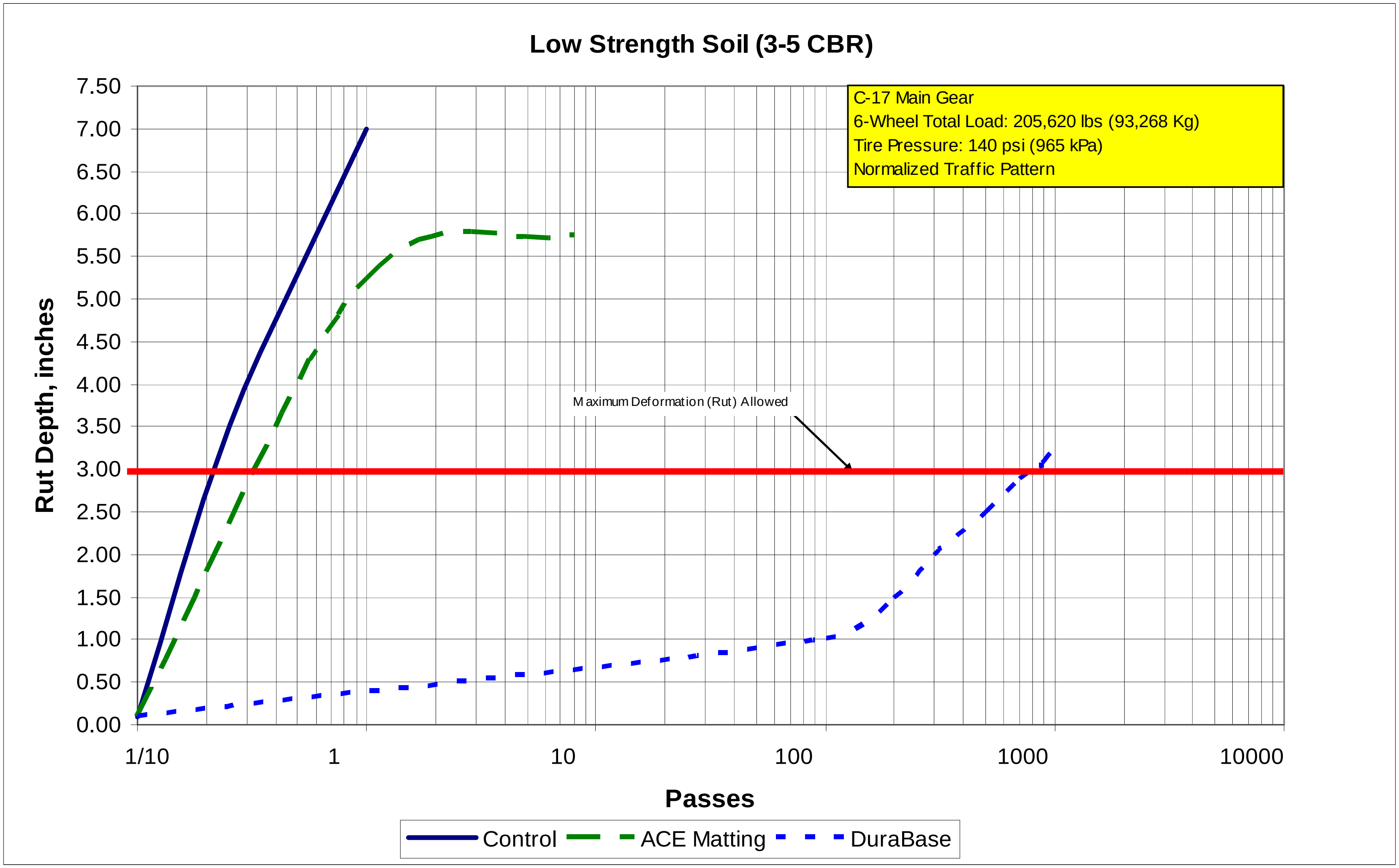

Figure 18. Deformation (Rut Depth) of Matting Systems on CH Soil Test Section

Photo 27. Silty Sand Control Test Section After Rutting Failure

Photo 28. High Plasticity Clay (CH) Control Test Section After Rutting Failure (1 Pass)

The final deformation (rut) depth recorded for the DURA-BASE® on the CH test section was 3.25 in. at 1001 passes. Failure due to rutting [≥76.2 mm (3 in.)] was achieved at 800 passes. Although not as beneficial as when applied to the SM test section, when compared to the CH control test section, the use of DURA-BASE® on a low strength soil does offer a significant increase in traffic load-carrying capacity. Again, if the issues of logistics and handling are insignificant, this matting system would be a good choice for use in low strength soil scenarios.

Photo 29. DURA-BASE® Being Subjected to Traffic on the SM Test Section

ACE-Mat™

The ACE-Mat™ performed well on the medium-strength subgrade. The mat began to show a rut of 76.2 mm (3 in.) at approximately 500 passes, with a 76.2-mm (3-in.) rut reported over most of the test section length at 561 passes. There was some minor pin shifting and a few pins were lost during trafficking. A few edge breaks were

also witnessed on the mat layout during trafficking, but all damage was well below the 20 percent threshold.

On the low-strength subgrade, the ACE-Mat™ offered little benefit compared to the control test with no matting applied. After only one pass, the mat achieved a permanent deformation of 146 mm (5.76 in.). This rut remained about the same after eight passes, but significant connection pin and mat breakage (greater than 20 percent) occurred, and the mat was failed. The clear result is that ACE-Mat™ will not support C-17 aircraft loads over low-strength soil conditions. Photos 30 and 31 show ACE-Mat™ on the SM test section and damage of the ACE-Mat™ on the CH test section, respectively.

Photo 30. Trafficking of C-17 Full Gear Load Cart on ACE-Mat™ Placed on SM Test Section

Bravo® Mat

Bravo® Mat, the second generation of a prototype design originally designated SP-12, exhibited improved characteristics over its prototype. Bravo® Mat has been utilized in the United States and the Middle East for applications such as flooring system for tents and temporary building systems, road surfaces for light (ATV and pickup truck) traffic, and as a dry surface for storage. Under the application of C-17 wheel loads, this mat did not perform as required.

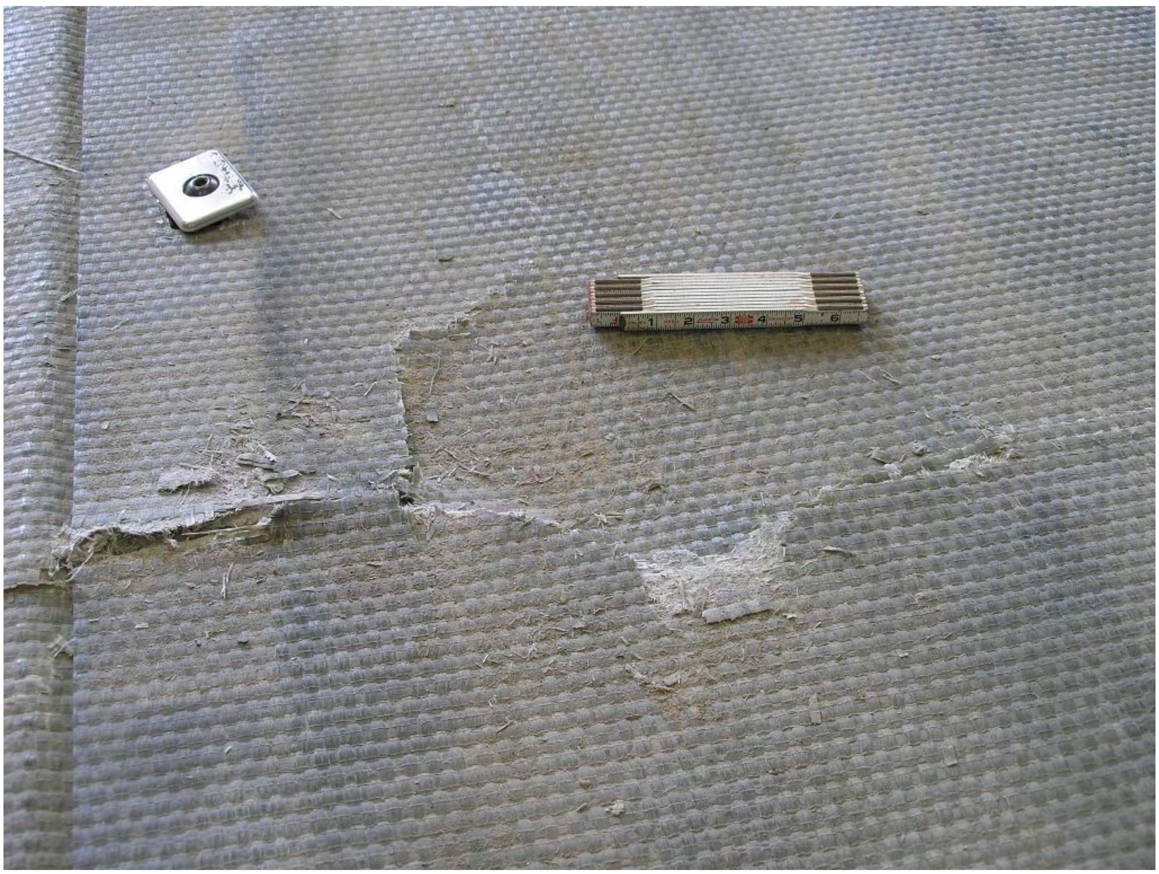

Photo 31. Typical Connection Pin and Mat Damage of the ACE-Mat™ on the CH Test Section

Failures included delamination of the mat skin from the mat skeleton, with associated mat breakage. As a result of these types of failures, the interior structure of the mat could be examined. During testing of the first generation of this matting (SP-12), delamination was determined to be caused by poor quality vibratory welding of the skin to the skeleton system. During the manufacturing process, it was believed that between 70 to 80 percent weld efficiency was achieved. After delamination of the SP-12 began, it was visually estimated that the efficiency was closer to 30 to 40 percent. With the Bravo® Mat the vibratory welding technique had been greatly improved, with what appeared to be 85 to 90 percent weld efficiency. Unfortunately, even with this vibratory weld efficiency improvement, the mat did not support the C-17 aircraft traffic.

With the Bravo® Mat installed on the SM test section (Photo 32), only 61 passes were required to declare the mat failed. Well over 20 percent of the mats installed showed delamination (Photo 33), cracking, breakage, or a combination thereof. The mat never achieved failure in rutting, with only about 25.4 mm (1 in.) of rutting after the 61 passes. Based on these results, the Bravo® Mat was not tested on the CH test section, and this mat would not be recommended for use under C-17 aircraft traffic on any soil condition encountered.

Photo 32. Trafficking on the BRAVO® Mat on SM Test Section

Photo 33. Delamination Failure of the BRAVO® Mat While Installed on SM Test Section

CHAPTER IV

MODELING PERFORMANCE OF MAT-SURFACE AIRFIELDS

Introduction

The literature review showed a long history of airfield matting systems being evaluated for response and performance under various types of loading. Since the first matting designs were produced, test sections have offered the most straightforward approach to the evaluation of matting systems.

For many years, the evaluation of concrete mats, or slabs, was performed in similar ways. It was not until engineers and mathematicians such as Westergaard and Skarlatos began predicting stresses and deflections that there was interest in modeling of such systems. The greatest hurdle at the time was the massive calculation effort required to derive and complete the equations within the solutions. Most of these solutions were not utilized because of the effort required, and the default was to use full test section performance data developed over many years of test section work. This approach continued until the advent of computers. With the recent development in faster processors, a laptop computer now handles very complex equations and solutions. This technology leap has revived many of these once unused solutions and concepts of years past. These concepts and solutions have formed and continue to form the basis for many of the models that are now used on a regular basis today.

The modeling of concrete pavements or slabs is based on the work of Westergaard and Skarlatos. Improved methods have been developed and are presented in very user-friendly programs such as J-Slab, EverFE and ISLAB or ILLISLAB. The theories and research of V. J. Boussinesq formed the basis of the layered elastic analysis (LEA) of homogenous, non-jointed pavements, such as asphalt roadways and airfields. Models such as WinJULEA were developed to give the user a simple means of applying the LEA techniques to the design of pavement systems (Wang et al., 2006).

Modeling of pavements, even in terms of relatively simple models presents a large accomplishment in pavements engineering. These models, when calibrated and checked for accuracy, provide a tool to evaluate future pavement concepts. For example, in the research field, this can mean dramatic savings by reducing the number of test sections required for a particular research effort. In the public and commercial applications, models can save both construction and maintenance dollars by predicting response of new pavement designs and providing some indication of long term performance.

The question posed is: Can a simple model be used to predict initial response of a matting system on a specified base soil? If so, is it reasonable to believe that this initial response can offer a glimpse of a matting systems' potential performance under traffic? As White and others have shown, modeling of matting systems is a complex phenomenon. Matting can be constructed of various materials, including fiberglass, plastic, aluminum, expansive foam, and in many cases, the matting system is a combination of these components. Unlike concrete and asphalt, matting systems are somewhat of an anomaly. They don't act exactly like concrete slabs, even though they

may resemble them, and they don't act exactly as an asphalt pavement, even though they tend to transfer a load similar to asphalt.

Modeling Approach

Several models were considered for use in this research, including ISLAB, JSLAB, EverFE, and WinJulea. However, two models, one that would bring the concrete slab pavements to the picture, the other, asphalt pavements, were chosen.

The two models selected were ISLAB2000, used for concrete slab pavement evaluation, and WinJULEA, designed to evaluate flexible pavements such as asphalt. Each model is well known and excepted in the engineering community, and both offer a means to model initial mat response and compare these responses to those of the full scale test sections, described in the previous chapter. Furthermore, by comparing the model response to the initial mat response on the test section, some conclusions on the validity of one or both models and their potential use in predicting mat system performance can be formed. This same technique could be applied as well to future prototype matting systems.

Modeling of matting systems, especially if initial evaluation efforts are minimal, can minimize the use of resources. By performing "first-cut" evaluations of a matting system through modeling, matting designs can be evaluated for various traffic loads with minimal effort and the need for further testing on a full scale level can be determined. Clearly, even small modeling efforts can add up to potentially big savings on the full-scale testing end.

ISLAB2000

ISLAB2000 is a plane stress format model. It employs a plate formulation of finite element analysis to model slabs as homogenous and elastic units. In general, any material that acts or can act as a plate could be analyzed using this model. ISLAB2000 can account for multiple, asymmetric surface loadings and is capable of modeling several different types of joint systems. The program allows for full, partial, or no bond between layers of material. ISLAB2000 uses modulus of elasticity to characterize the slab. In the case of mats, a "composite" type modulus, based on a four-point bending test performed on one mat alone and two mats connected together, is used. Base soils are characterized by the k (subgrade reaction) value of the soils, which can be assigned by the modeler, based on known information, or could be determined using a plate bearing test.

ISLAB2000 is capable of modeling several different types of joints. As discussed, ISLAB2000 was developed to model concrete slab pavements and so it was designed to simulate the types of joints found with these slabs. It is capable of simulating various joints found in slab pavements, including dowelled joints, aggregate interlock joints, or simple "contact joints" where the slabs touch one another, but there is little if any load transfer. Joints are simulated in the model using a spring, so a spring constant, k, is part of the joint calculations. Because of this flexibility, this model is ideal for performing some basic analysis of matting system joints and their predicted affects. For the modeling of mats, three joint setups were examined. These setups allow the full evaluation of mats, specifically for the joints, within the capabilities of the ISLAB2000 program. Each joint type was evaluated with the load placed in the center of the mat, along a longitudinal

joint of the mat, and along a transverse joint of the mat. The three joint types examined are described as follows:

- Rigid joints – both moment and shear transfer,
- 100% load transfer – simulates a hinge point with shear transfer only, and
- 0% load transfer – simulates the mat joint as being present, but allows no moment or shear transfer.

WinJULEA

WinJULEA is a Windows-based layered elastic analysis model. It uses elastic, isotropic, homogenous, layered materials of uniform thickness in its analysis. The layers extend horizontally to infinity and the bottom layer extends in the z-direction to infinity. Because it was developed primarily for asphalt pavements, it does not have the ability to model joints. It characterizes the materials by modulus of elasticity (E) and Poisson's ratio. As with ISLAB2000, this is a "composite" type modulus, based on a four-point bending test performed on one mat alone and two mats connected together. The soil modulus was determined by converting CBR to a dynamic modulus. The author used the conversion for this modulus presented by Heukelom and Foster (1960), which is discussed in the next section (Material Parameters and Traffic Simulation) of this chapter.

Like ISLAB2000, WinJULEA is capable of simulating full, partial, or no bond between layers. It is also capable of evaluating multiple, asymmetrical surface loadings. Unlike ISLAB2000, which can only calculate stresses in the slab layers, WinJULEA can calculate stresses at any elevation within the model. This is a critical factor in the use of

WinJULEA, since the full-scale test section analyzed in this effort made use of pressure cells at various depths (Chapter 3).

Assumptions

In order to perform the modeling of the matting systems tested here, a few assumptions must be made. Unlike the full-scale test section, the models assume perfect placement, both vertically and horizontally, of the instrumentation. The models also assume exact placement of traffic. The test sections are considered uniformly constructed, with no variation in materials or placement.

The ISLAB2000 program assumes that the Winkler Spring foundation will adequately simulate a soil foundation. This requires the soil bearing strength, typically represented by California Bearing Ratio (CBR), to be converted to a modulus of subgrade reaction (k). There are several mathematical relations between CBR and k, but none are considered exact, and the relation is basically empirical.

WinJULEA uses a modulus of elasticity to represent the soil foundation. Similar to ISLAB2000, this requires the conversion of the soil bearing strength (CBR) to, in this case, a modulus of elasticity. As with the k value, there is no direct transition, and the conversion is mostly empirical, with several accepted mathematical relations, all giving differing answers. The discussion of the conversions from CBR to k and E will be discussed in the next section (Material Parameters and Traffic Simulation) of this chapter.

Limitations

In addition to the assumptions discussed, the models also have limitations. One of the more significant is the ability to simulate traffic loads. Both models only simulate

static loads. More advanced three-dimensional modeling programs can simulate moving, or dynamic loads.

Another issue is accumulated deformation and damage to the matting systems. Elastic deformation only occurs when the load is applied, in this case, to the mat and soil. Once the load is removed, the soil and mat return to their original elevation and/or position. Both the ISLAB and WinJULEA can simulate this type of deformation. However, these models cannot measure rutting (accumulation of plastic deformation), which is the deformation of the matting system and the soil beneath it that remains, even after the load is removed. The same is true for damage, such as mat breakage and connection pin failure. These two factors, plastic deformation and damage, can play pivotal roles in the potential lifespan of a matting system.

Debris from mat breakage and pin failure can cause operational hazards to aircraft. This condition can lead to a “failed” rating for a mat, even if it is still supporting the load. On the other hand, plastic deformation (ruts) is an important measurement for aircraft operation. In the case of the C-17 aircraft, a rut in the traffic area equal to or greater than 76.2 mm (3 in.) would cause the mat to be given a “failed” rating. The mat may have no breakage or mechanical failure, but excessive rutting would end its application. Other factors such as weather conditions, temperature, and dynamic material properties can also dictate potential mat performance. These will not be discussed here.

Finally, joints can be simulated within the ISLAB2000 model. However, it is important to understand that the ISLAB2000 program “simulates” these joints as part of the whole mat itself, it does not “model” the joints, such that stresses and strains of the joint itself can be analyzed. ISLAB2000 uses springs to simulate the mat joints, using a

spring constant, k. There are more complex three-dimensional modeling programs, such as Abaqus, that can more precisely model mat system joints.

Material Parameters and Traffic Simulation

In order to utilize ISLAB2000 and WinJULEA models, there are several important pieces of information needed as input into the model. They are modulus of elasticity of the mat and the soil foundation, Poisson's ratio for the mat in both models and for the soil foundation in WinJULEA, the foundation k value in ISLAB2000, mat dimensions, plan layout, orientation (ISLAB2000 only), mat thicknesses, and finally traffic load and orientation.

Modulus of elasticity for a matting system can only be precisely determined by examining all the materials used in the mat, their structure, orientation, dimensions, etc. and determining how each one contributes to the overall modulus of the mat. This is especially true with a composite mat, where multiple materials and structures can combine to produce the final mat. For the analysis of matting systems, this would be quite time consuming and require a large amount of resources to complete. In reality, an "effective" modulus of elasticity is sufficient for the purpose here. In this case, the "effective" modulus of elasticity is the modulus of a solid, homogenous plate that acts similarly to the mat being considered. This is further explained below. This "effective" modulus is determined by first performing a 4-point bending test.

The 4-point bending test is accomplished using one mat alone and two mats connected together using the mat jointing system. The mats are placed between two beams. Four deflection gauges are placed under the mat, starting at the centerline,

between beams, and spaced evenly between the centerline and beam (Photo 34). The mat is loaded evenly along the centerline by using a beam placed on the mat along the centerline to distribute the loaded weight (Photo 35). As the beam is loaded, the deflection basin is measured. The test is stopped at approximately 25.4 mm (1 in.) of deflection at the maximum point, or the centerline. Note that in Photo 34, the distribution beam has already caused some deflection. The weight of the beam itself was used as part of the load for the bending test.

Photo 34. Composite Modulus Testing on ACE-Mat™. The Loading Beam is Placed on Top. Note the 4 Deflection Gauges Below. The Mat was not Deflected before Placement of the Loading Beam, which was included in the Deflection Weight

Once the bending test is complete, the deflection measured is compared to the solution derived from the complex set of equations commonly referred to as the plate equations as described in detail by Murphy (1935). A computer program or finite element code can be

used to easily solve this complex set of equations. By knowing the mat dimensions and thickness, the dimensions of the bending test setup, loading weight used, assigning a Poisson's ratio, and arbitrarily picking a modulus of elasticity, the plate equations can be solved for the deflection of the mat. By varying the only factor that is not known, modulus of elasticity, the deflection given by the plate equations is varied until the plate equation solution for deflection and the field measured deflection match as closely as possible. The modulus of elasticity that achieves this match is the "effective" modulus of elasticity value.

The plate equations are comprised of a large set of equations that will not be discussed here. However, the key equation utilized is the flexural stiffness or plate stiffness equation as follows:

$$D = \frac{Et^3}{12(1-\nu^2)} \qquad (4.1)$$

In this equation, E is modulus of elasticity, t is thickness of the mat (plate) and υ is Poisson's ratio of the mat. The only unknown is E. By varying E, as discussed above, we can solve the plate equations and vary the solution for mat deflection, which leads to the comparative solution of modulus of elasticity, in this case an "effective" modulus of elasticity, for the mat tested.

The "effective" modulus of elasticity is determined for one mat and then for two mats connected together using the connection system employed by the mat. In this work, the joint was oriented perpendicular to the load, as this is how load would typically be applied in field installations. The "effective" modulus of elasticity values for one and two mats are compared and the lesser, or more conservative, of the two is assigned as the

"effective" value for the mat being tested. Table 5 shows the pertinent information on the testing of each mat. The modulus values in red were used in the model analyses.

Photo 35. The Composite Modulus Testing on Bravo® Mat. Note this Load is Approximately 1,270 kg (2,800 lb)

Table 5. Mat Data Used to Calculate Composite Elastic Moduli. The Values in Red Were Used in the Models

MAT	MATERIAL	PANEL SIZE	MAT TEST CONFIGURATION	DIRECTION OF TESTING	UNIT THICKNESS (IN)	MODULUS ELASTICITY (PSI)	POISSON RATIO
BRAVO	HDPE	4' BY 4'	1 MAT	LONG	2.75	26400	0.3
BRAVO	HDPE	4' BY 4'	2 MATS CONNECTED	LONG	2.75	17200	0.3
ACE-5PLY	FIBERGLASS	6.67' BY 6.67'	1 MAT	LONG	0.375	2460000	0.2
ACE-5PLY	FIBERGLASS	6.67' BY 6.67'	2 MATS CONNECTED	LONG	0.375	1700000	0.2
DURABASE	HDPE	8' BY 14'	1 MAT	LONG	4.0	46500	0.3
DURABASE	HDPE	8' BY 14'	2 MATS CONNECTED	LONG	4.0	67000	0.3

The modulus of elasticity of the soil (Young's Modulus, E) can be determined using one of several relations developed over the years relating E to soil CBR. Heukelom and Foster (1960) plotted three sets of data that related E to CBR. Two sets of data used wave velocity measurements to determine the E value. The third set used soil stiffness values to determine E. The grouping of the data showed that the average correlation for CBR and E value was related by:

$$E = 110(CBR) \qquad \text{(E in units of kg/cm}^2\text{)} \qquad (4.2)$$

$$E = 1500(CBR) \qquad \text{(E in units of psi)} \qquad (4.3)$$

In order to bound approximately 95 percent of the data (about 6 of the points become outliers) Heukelom and Foster stated that the factor of 110, used in the first equation above, would very from about 50 to 200. Yoder and Witczak (1975) referenced Heukelom and Foster in their book, and stated that the equation above, in its second form listed, is one of the most widely used correlations in engineering practice. As eluded to in discussions of the variance in the factor, Yoder and Witczak also cautioned that there was variance in this correlation and this should be understood in its use. Based on the factors suggested, this correlation would convert a CBR of 9 that is representative of the silty

sand material in one of the test sections, to a Young's modulus of 93,079 kPa (13,500 psi), with a potential range of 38,610 to 186,158 kPa (5,600 to 27,000 psi).

In a sensitivity study using both WinJULEA and ISLAB2000, it was determined that in varying the E value used in the WinJULEA model, both models agreed in terms of deflection when the WinJULEA model used an E value of 41,368 kPa (6,000 psi). This value of 41,368 kPa (6,000 psi) is within the allowable range of values, and was therefore determined acceptable. Additionally, another project within JRAC, focused on soil testing and classification, involved numerous tri-axial tests on the same silty sand material. The resulting data will be published in an ERDC report in 2008. In the analysis of the test data, the shear stress/shear strain curves were evaluated at the small strain (linear) portion of the curves. It was assumed at small strains that the modulus determined was close to elastic behavior. This elastic shear modulus was converted to Young's modulus using a Poisson's ratio of 0.4, as was chosen for this model evaluation effort. With confining pressures of 103 to 345 kPa (15 to 50 psi), Young's modulus values of 25,579 to 62,052 kPa (4,000 to 9,000 psi) were determined, once again confirming the validity of the chosen 41,368 kPa (6,000 psi) value (Berney, 2007).

Poisson's Ratio describes the property of a material that when deformed (tension or compression) in one direction, it tends to become deformed in the opposite manner in the other two directions. In more technical terms, the ratio is one of relative contraction strain, or transverse strain (normal to the applied load) divided by the relative extension (axial) strain in the direction of the applied load. Poisson's ratio can vary from 0.0 (cork) to 0.3 (steel) to 0.5 (rubber). Because these mats were either polymer composite types (Bravo and DURA-BASE) or fiberglass ply (ACE-MAT), the ratio would likely fall in

the range of 0.3 and 0.4. The author chose a value of 0.35 for the modeling efforts here. The silty sand base soil material was given a ratio of 0.4.

The k value of a soil is also known as the modulus of subgrade reaction. This term is typically used with many pavement modeling programs, such as ISLAB2000, to represent the stiffness of the base soil materials below the pavement structure. There are several equations that have been proposed to convert the CBR value of a soil to a k value. These are typically based on databases of previous laboratory tests or test section measurements, and as such, are highly empirical. Typical values of k for a silty sand soil are between 100 and 200. Hall and Elsea (1974) produced a plot of soil reaction (k) versus CBR. For the silty and clayey sand materials, they found that a CBR value of 9 produces a k value of approximately 190. The analysis of various soil databases and mat test sections indicated that a k value of 200 for a silty sand soil with a CBR of 9 was acceptable. At the time of this research effort, other efforts within the JRAC program were focused on developing models to estimate soil strengths and potential aircraft traffic capabilities. This modeling effort within JRAC is scheduled for publication sometime in 2008. (Gonzalez and Barker, 2007)

Further validation of this k value of 200 can be seen when the conversion of the k value to a modulus of elasticity is performed. Parker and Barker suggested a conversion equation in 1979:

$$\log(MR) = 1.415 + 1.284\log(k) \qquad (4.4)$$

where:

MR (or resilient modulus) = the modulus of elasticity

k	=	the modulus of subgrade reaction
Log	=	base 10

When the k value of 200 is inserted, the resulting answer is 24,416 psi. This value falls within the 95 percentile range of a CBR of 9, as suggested by Heukelom and Foster (1960). As discussed before, these conversions for CBR to modulus or subgrade reaction are mostly empirical, and subject to some interpretation. However, based on the sensitivity study done here, the literature consulted, and the information given by the interviewed researchers, the values of 41,368 kPa (6,000 psi) for the modulus of elasticity and 200 for the subgrade reaction of a silty sand material are reasonable.

Since WinJULEA is an elastic continuum model with no joints, no mat layout is required to run this model, only mat and soil material parameters and thicknesses are needed. For the ISLAB2000 model, the number of mats used in the test section perpendicular to traffic was needed, in addition to the other parameters listed. The number of mats parallel to traffic was varied, with 11 used for the Bravo® mat, 7 used for the ACE-Mat™, and 6 used for the DURA-BASE® matting. The mat dimensions used in the ISLAB2000 program were taken from the mat information presented in Chapter 3 of this thesis.

The C-17 loading was represented in both ISLAB2000 and WinJULEA using the layout presented in Figure 19. Only one main gear was simulated. The figure below shows both gears. Tire pressures are 965 kPa (140 psi).

For WinJULEA, placement of the load is not critical, as model conditions, horizontally, will be the same, since this is an elastic continuum model, and there are no joints. For the ISLAB2000 model, three different gear positions were examined. The gear

was first placed as close as possible to the middle of the mat. For the large DURA-BASE® mat, this was easily done. For the BRAVO® mat and ACE-Mat™, the gear was positioned such that each tire was as close to center of a corresponding mat as possible. With the large gear set and smaller mats, this meant that the gear was actually placed over several mats simultaneously. The second position was placing the gear as close as possible (within a few inches) of a longitudinal joint (parallel to the direction of traffic). This meant moving the gear and placing one side of the gear near the joint, with the rest of the gear placed on the mat or several mats, depending on which mat was being modeled. The final position was placing the gear as close as possible to a transverse joint (perpendicular to the direction of traffic). Placement of the gear was done in a similar fashion to that used with the longitudinal joint.

Comparisons of Model Results

With the selection of ISLAB2000 and WinJULEA as the models to analyze, runs for all three mat types and the possible gear positions were performed. In order to determine the validity of one or both models, a general evaluation procedure was followed by the author.

The first step was to determine the effect of the matting system joints on the deflection potential and internal tensile stresses within the various mats. ISLAB2000 allows the various joint types, as discussed in the “Modeling Approach” section of this chapter, to be simulated and analyzed. In addition, three different gear positions for each joint type were also simulated. The various joint types and gear positions were compared for each mat. The final results indicated that indeed the joints of the matting systems, in

general, had little effect on the deflection potential or internal tensile stresses with each of the matting systems.

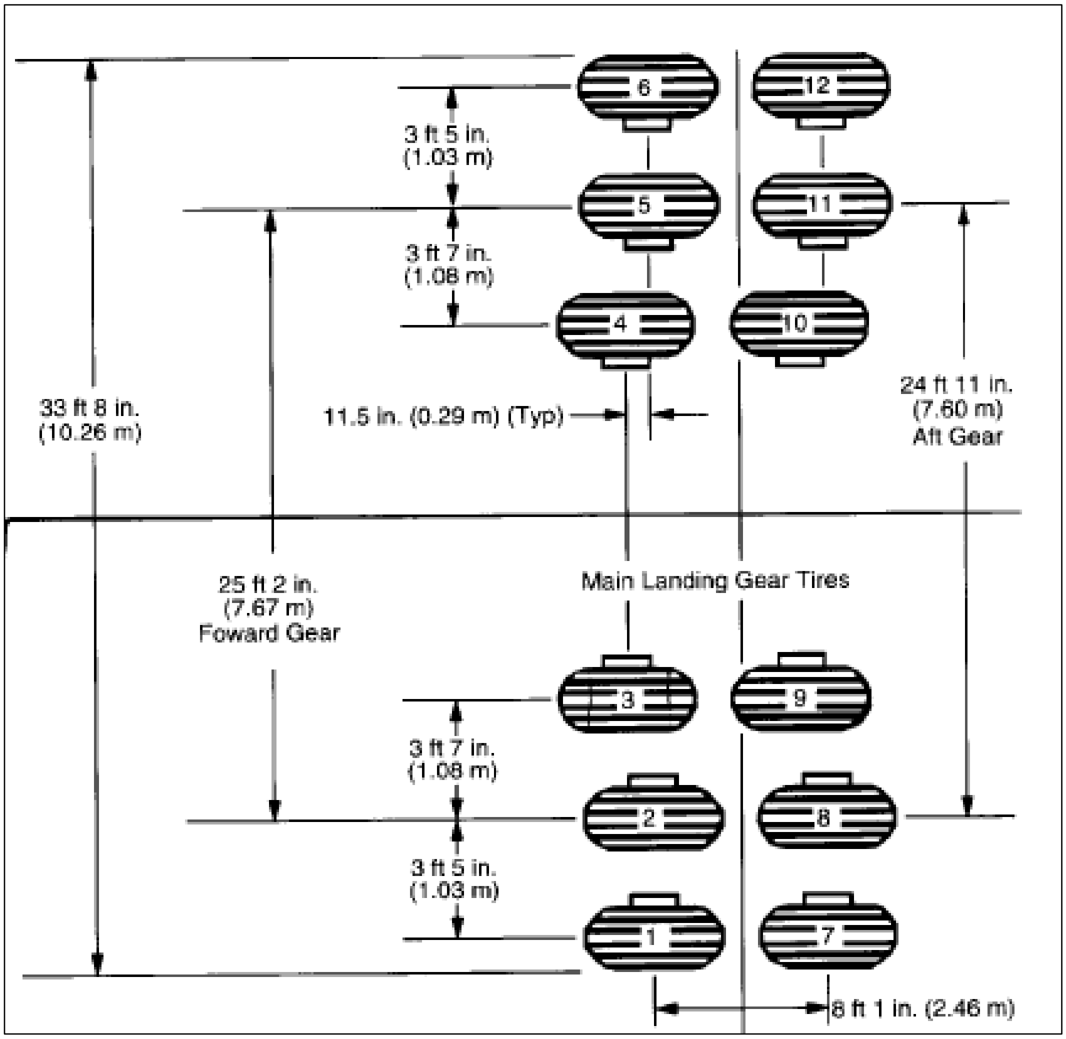

Figure 19. Dimensions of the C-17 main gear. Note that only one main gear is simulated in the models. (After Air Force Civil Engineering Support Agency, ETL 97-9, 1997)

Figures 20 through 22 compare deflection of the matting systems versus gear position and then joint type. The differences between gear positions for one joint type are typically not more than a few hundredths of an inch, with some being near zero. The

same trends are seen when comparing different joint types within a gear type and between gear types. Figures 23 through 25 show the comparison of internal tensile stresses within the mat while loaded. Again, it is clear that the joint configuration for a given loading position makes little difference in the induced tensile stresses in the mat. Even further, there seems to be little difference in the induced stress with different loading positions for the same joint types are compared. There was one spike in the tensile stress results for the ACE-Mat in the longitudinal loading position with a rigid joint. The maximum tensile stress in the y-direction along the top of the mat was about 12,410 kPa (1,800 psi) higher than the other joint types within the longitudinal gear position plots. It was also about 12,410 to 16,547 kPa (1,800 to 2,400 psi) higher than any of the other joint/load position plots. The reasoning for this value difference is not entirely clear, but a very small difference in the loading position (human error) in this run versus other, similar runs, could be one potential cause.

The results of the ISLAB2000 modeling clearly show that the joints of the various matting systems tested here play minor roles in the matting systems' response to load. This result is important. By determining that the joints have little effect on the response of the matting systems, it can be concluded our evaluations can be performed with a less complex model requiring less effort. It is important, however, to understand that the mats evaluated here all utilized the overlapping/underlapping type joint. Further testing with other mat joint types are needed to determine if this finding would apply to all mat joints in general.

Modeling the matting systems using the WinJULEA model is somewhat less complex than with ISLAB2000, in that the input and results are simpler and all displayed

on one window on the computer screen. In addition, the run time of the WinJULEA program is much less than that of ISLAB2000. However, in order to validate use of WinJULEA as compared to the ISLAB2000 model, there needs to be a means of comparing the response of the two to a common load and base soil condition. Since WinJULEA is a completely different model from ISLAB2000, and since it simulates the foundation soils in a very different way, comparisons of such parameters as tensile stresses or forces within the mats is not valid. In addition, unlike WinJULEA, ISLAB2000 does not calculate stresses or strains in the foundation soils, only in the matting systems. So a direct comparison of soil stresses is not possible. The best comparison between the two for a check of response validity of WinJULEA compared to ISLAB2000 is deflection.

Figure 26 graphically shows the average maximum and minimum deflections of the matting systems as tested in the ISLAB2000 model as compared to the same systems tested in the WinJULEA model. There is some difference between the two models. This is expected as both models are very different. Clearly, ISLAB2000 predicts higher deflections of the matting systems, and since this model simulates the foundation soil using a spring constant, this is a logical prediction. The spring mechanism is much more flexible than the elastic continuum used by WinJULEA and therefore is expected to predict a higher deflection than the elastic continuum mechanism. It is important to note that the WinJULEA deflections only differ by a few tenths of an inch when compared to the ISLAB2000 deflections, and in airfield mat modeling, this would be a more than acceptable margin of error.

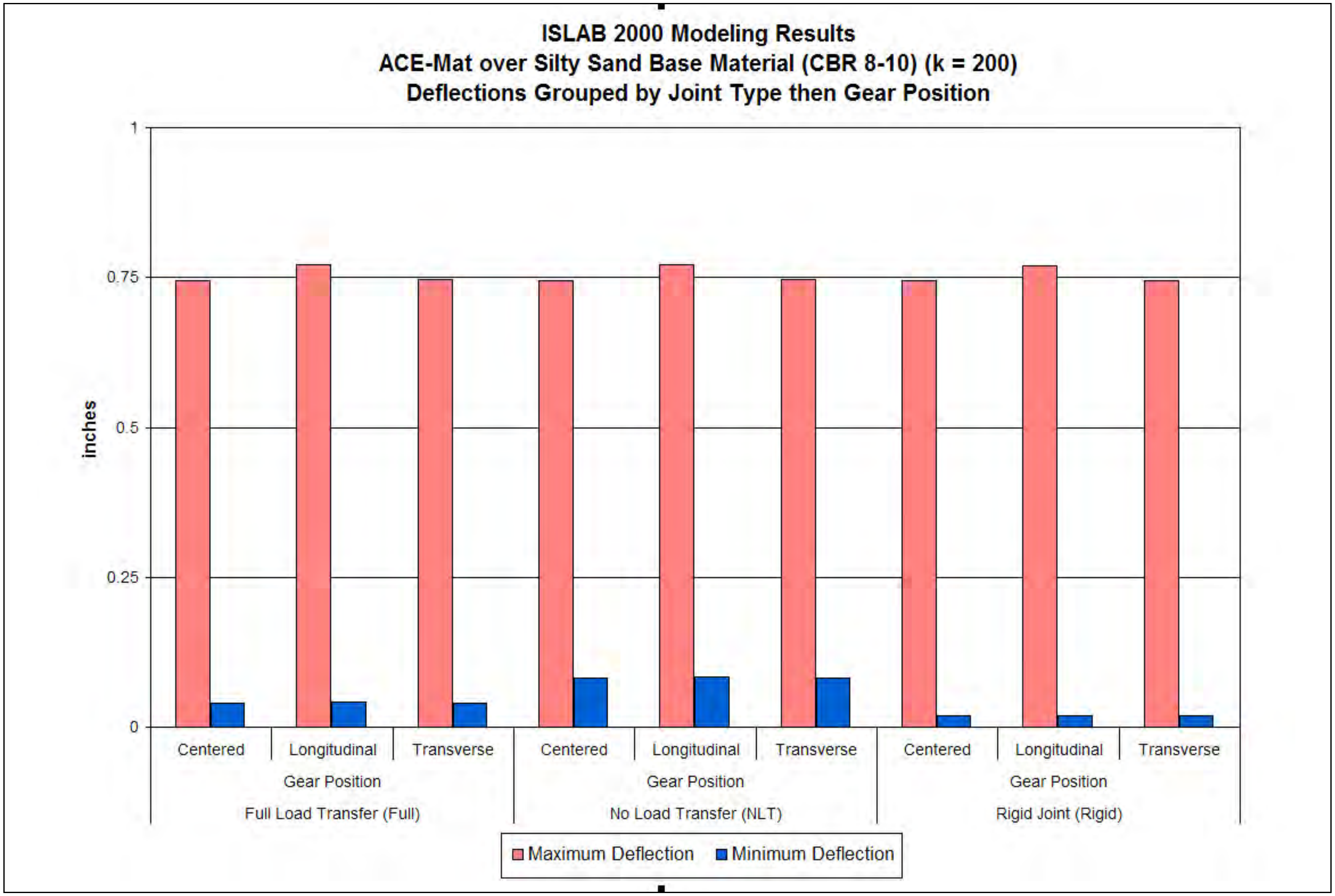

Figure 20. Deflection Results of ACE-Mat™ by ISLAB2000

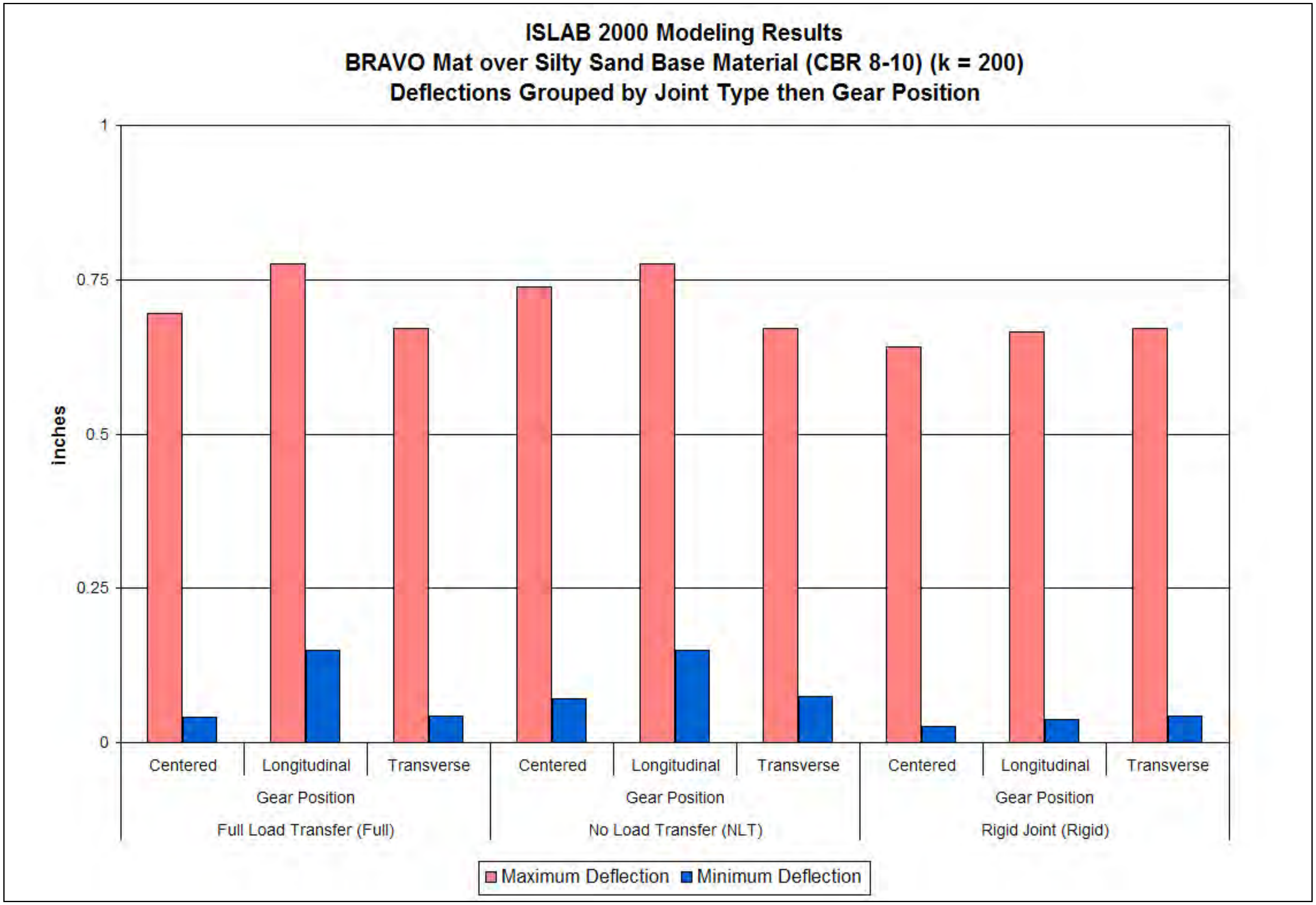

Figure 21. Deflection Results of BRAVO® Mat by ISLAB2000

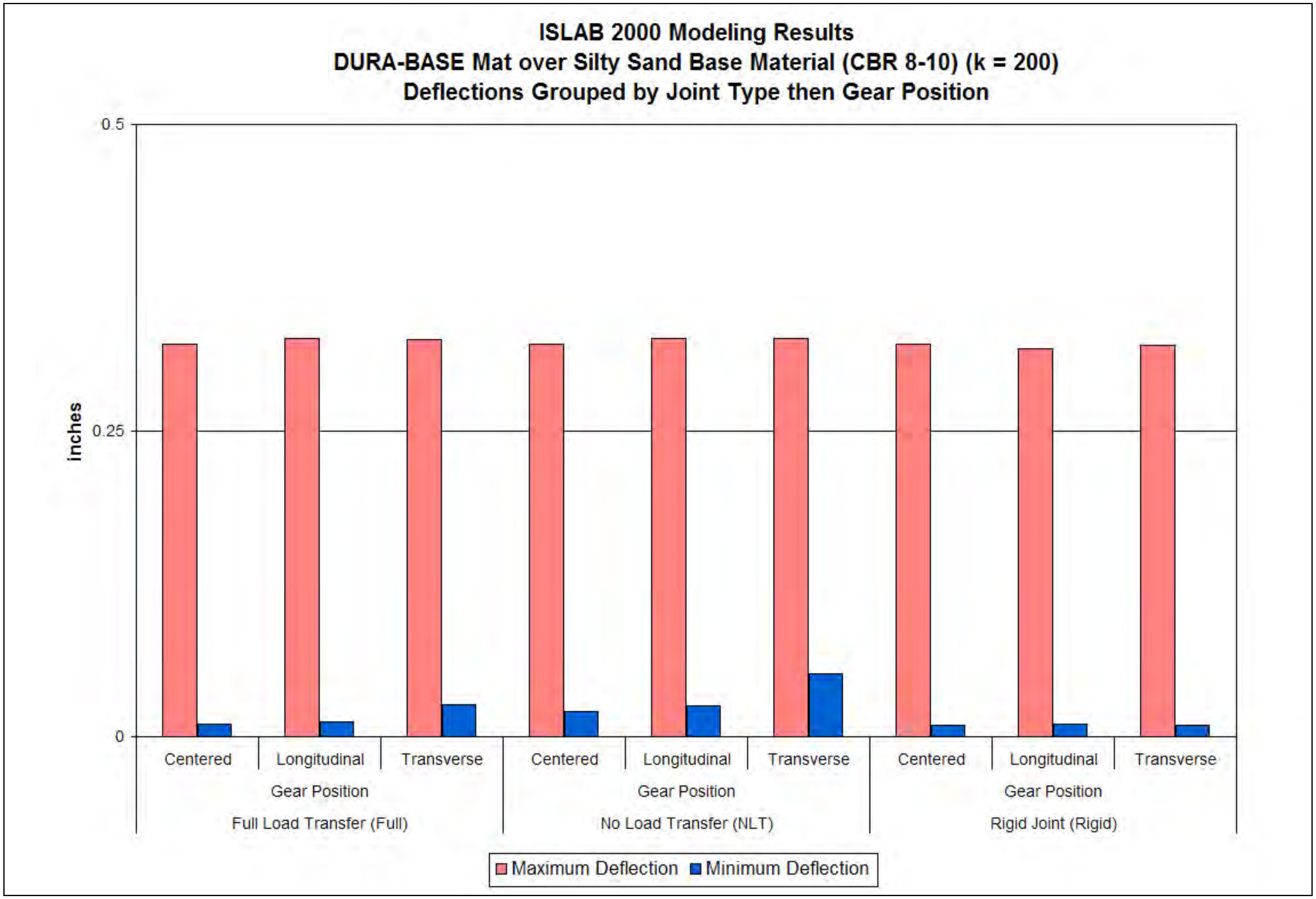

Figure 22. Deflection Results of DURA-BASE® Mat by ISLAB2000

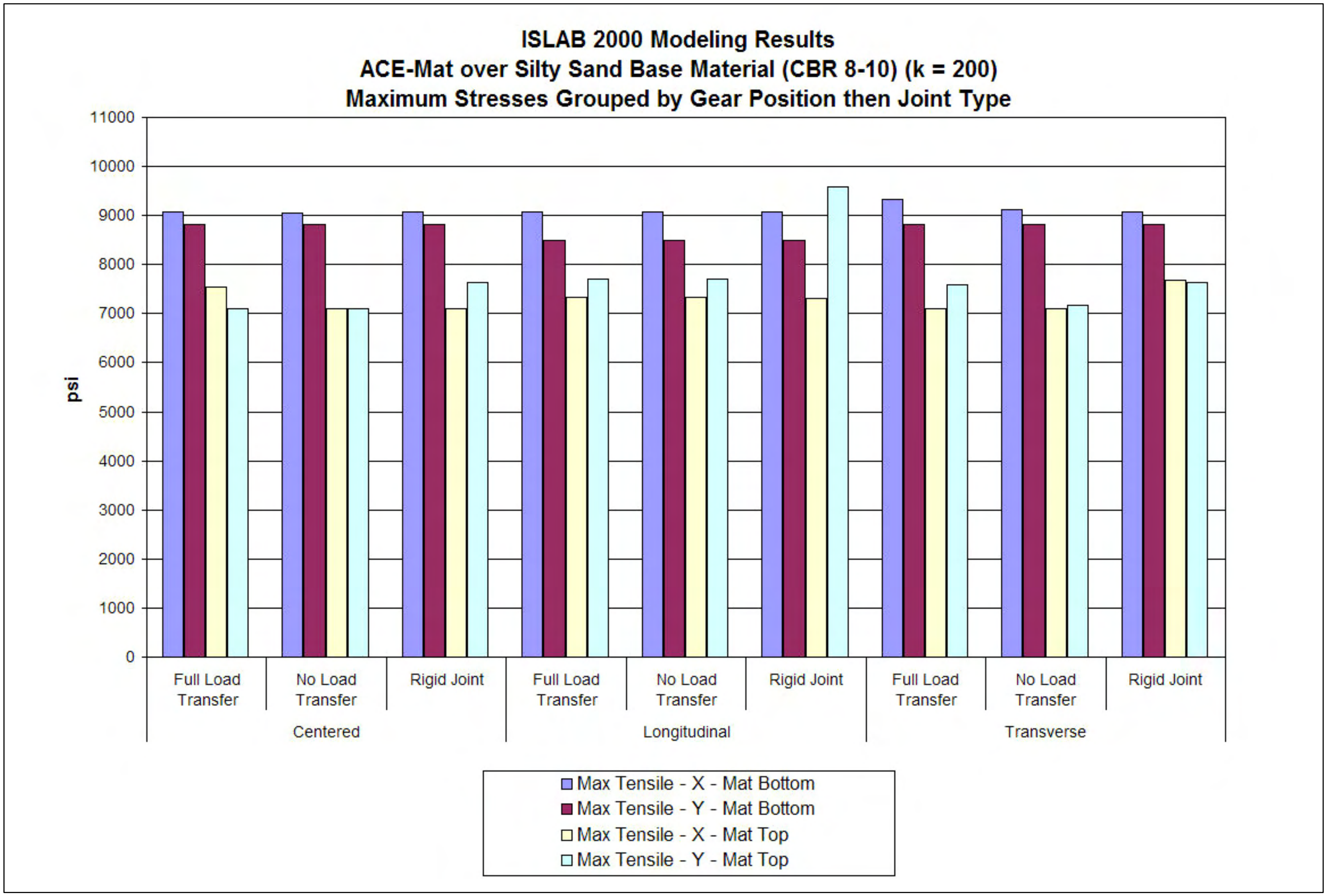

Figure 23. ACE-Mat™ Tensile Stresses by ISLAB 2000

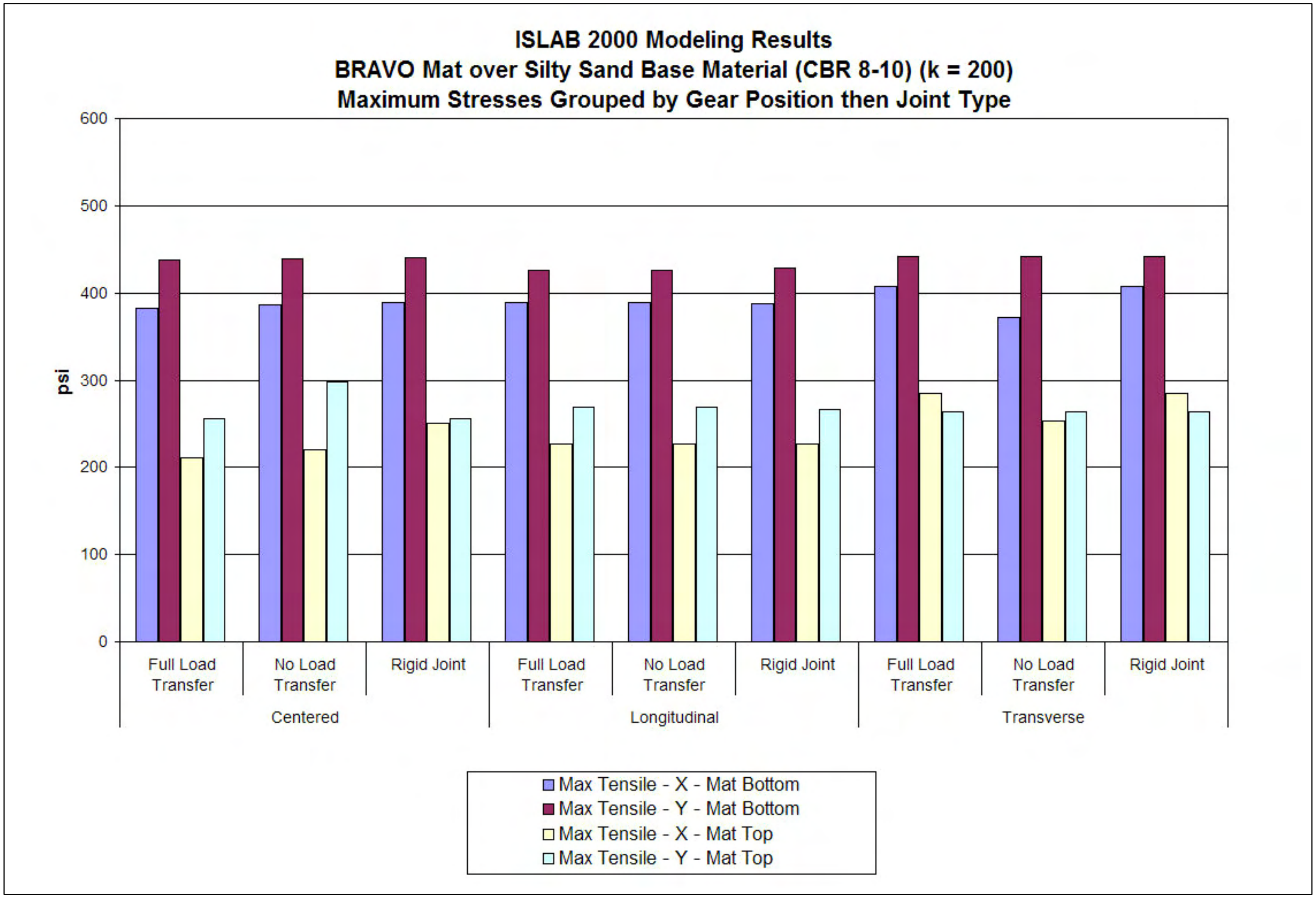

Figure 24. BRAVO® Mat Tensile Stresses by ISLAB2000

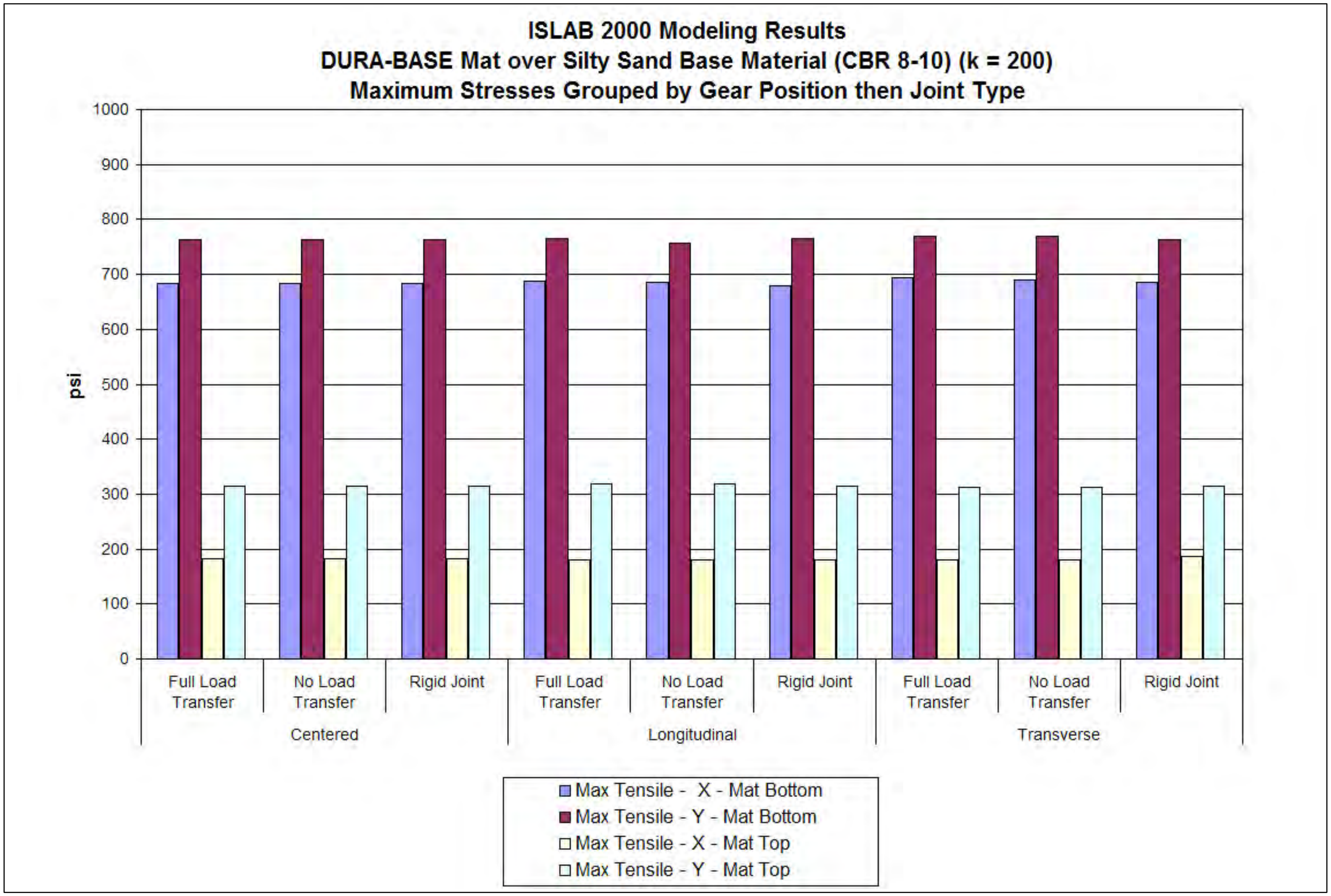

Figure 25. DURA-BASE® Mat Tensile Stresses by ISLAB2000

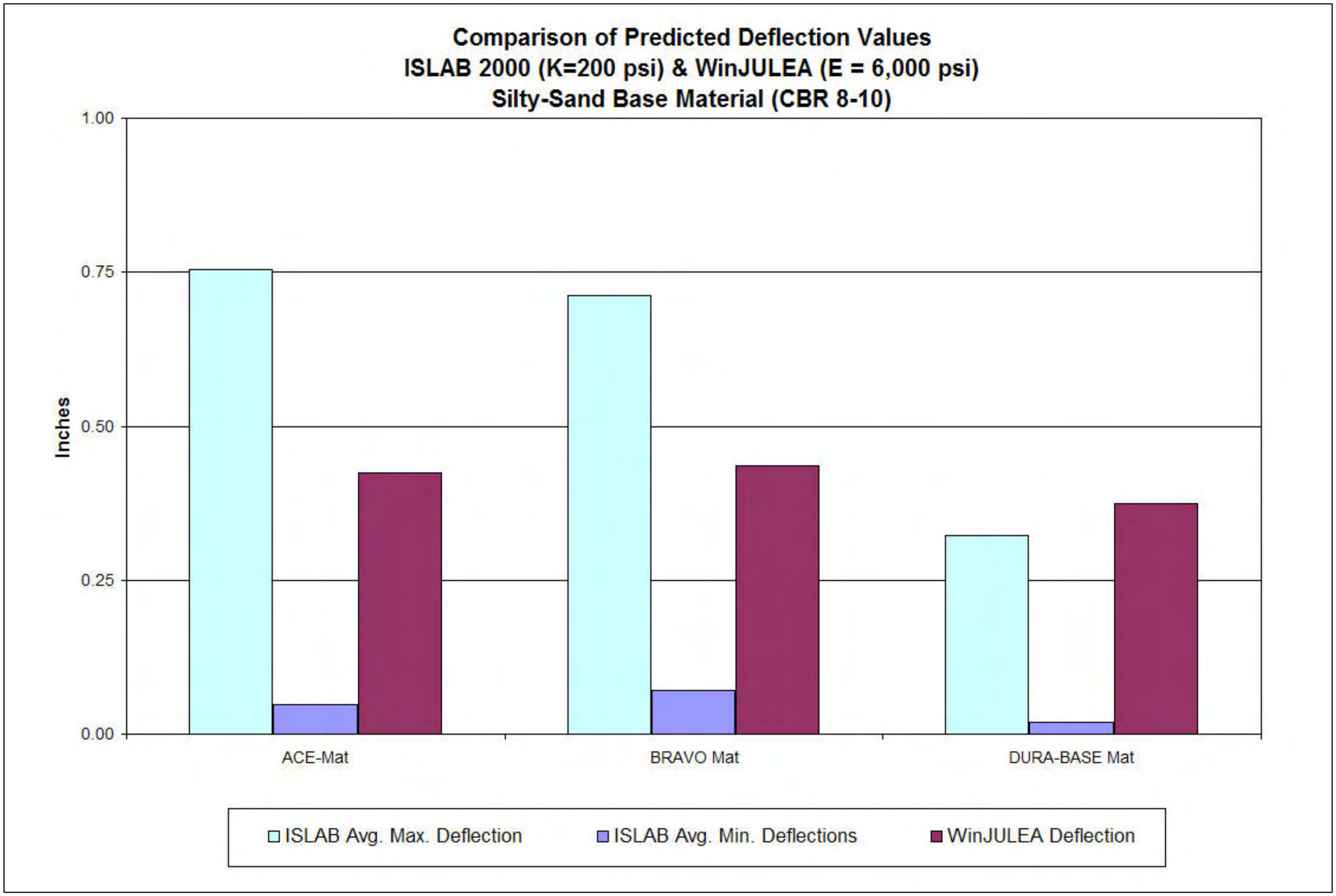

Figure 26. Model Loaded Deflection Comparisons

Because of the deflection results described above, an election was made to use the WinJULEA model for the final analysis. Having determined to use WinJULEA based on joint response and deflection predictions of both models, the final step was to validate the response of the WinJULEA model. Validation was performed by comparing the responses predicted by the model to the initial response of the matting systems when evaluated on the full-scale test section.

Predicted Versus Measured Response Under Load

In the actual test section work, only plastic deformation (rutting) was measured, as this, as well as mat damage, was the test section criteria. Both the models evaluated measured the deflection as a response to loading. This deflection includes both elastic and plastic deformation. With the test section, once the load is removed, only plastic deformation remains. Because the models predict initial response to loading (plastic and elastic), they cannot be fully validated by the test section rut depth (plastic deformation) data.

The full-scale test section work did include the installation of several pressure cells (Chapter 3, Instrumentation). Since WinJULEA can predict stresses at any point in the model system, from the surface to any depth below, it is relatively simple to set the model evaluation points at the depths of the pressure cells of interest. The assumption was made that the readings from pressure cells in the full-scale section were produced when the load cart's wheel traveled directly over the cell's position, producing the maximum pressure recorded. Since all the pressure cells examined here were positioned along the longitudinal centerline of the full-scale test section, the recorded cell readings

were taken as the load cart traversed this center lane. It is further assumed that the load cart traversed this center lane in a straight line, such that the center tires of the load cart produced the cell’s maximum pressure reading. These assumptions are important because precise position of the load cart, other than traveling in the center traffic lane, was not documented during the test section work. If the cart was not centered in this lane during the pass in which the pressure cells were activated, the readings obtained could be different. This difference comes when the “load cone-of-influence” below the tire and into the soil is in a different position, other than centered over the load cell. If only a fraction of the cone falls over the cell, then only that fraction of the load influence is captured. With multiple tires, it is clear how this movement of the cones from other than the center of the test section lane is further complicated.

Table 6 compares the responses of several pressure cells from the first pass of the load cart (initial responses) on the silty-sand (CBR = 9) full-scale test section to the predicted pressures at the same positions in the WinJULEA model. There are a few limitations in the data that should be explained first. For the HP2 cell there were some operational errors under the Control and DURA-BASE test runs. This cell was repaired for the ACE-Mat™ and BRAVO® mat runs as evidenced by the more reasonable readings that were obtained compared to the first data recorded and when compared to the readings of the pressures cells located above and below in elevation to HP2. The HP4 cell was not installed on the Control and DURA-BASE® test runs.

Even with the above limitations, in general, the pressure cells compared favorably to the model predictions. Very close to the boundary conditions (near the bottom of the mat, 152 mm or 6 in. depth), the predictions differ from the cell readings. However, with

only two cells to compare, it could be argued this is not enough data to fully deny the accuracy at this level. The predictions of the model are reasonably close in most cases to the test section results. The model did, almost consistently, predict lower pressures than the test section produced. There are several possible theories for this trend, including: the soil above the cells could have had higher moisture levels than the surrounding soil, resulting in higher compressions, the traffic patterns could have been slightly off in position during pressure cell logging, or there could have been hardened balls of soil or rocks inadvertently deposited on or near the pressure cell surfaces.

Table 6. Comparison of Silty Sand Test Section Pressure Cell Responses to WinJULEA Predicted Responses

	Silty Sand, Full-Scale Test Section - CBR = 9									
Gauge Number	HP4	HP1	HP2	HP3	LP1	WinJULEA - Subgrade Modulus = 6,000 psi				
Depth Below Mat (Inches)	6	12	21	30	42	6	12	21	30	42
Test Item	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)
Control Test Section	N/A	100.8	1.5	25.9	11.8	95.10	60.30	30.40	18.60	12.20
DURA-BASE Test Section	N/A	35.5	0.0	20.0	9.1	69.20	45.70	26.00	17.30	11.90
ACE-Mat Test Section	109.0	81.3	35.1	30.5	11.2	95.40	59.80	30.20	18.50	12.20
BRAVO Mat Test Section	42.9	68.5	34.1	20.3	10.1	94.40	58.80	29.90	18.50	12.20

Even with the above described conditions, the model generally agrees with the recorded pressure cell data. There are some differences between the model and recorded values, and this would be the expectation with any model. Slight changes in any of the input values could cause the model to be more or less accurate, but these types of sensitivity studies are beyond the scope of this study. The important conclusion here is that at most of the data points, the model and the test section compare favorably, and the model results display similar trends to the actual recorded data.

Summary

The modeling effort began by justifying the selection of various values needed for the modeling effort. These values included mat “effective” modulus values, k (subgrade reaction) value and modulus of elasticity of the base soil. A Poisson’s ratio for the matting systems and base soil was chosen. The analysis began with the ISLAB2000 model. The first question was the effect of mat joints on load transfer, deflection, and mat stresses. The results showed that the joints (in this case overlapping/underlapping type) appear to make little if any difference in mat internal tensile forces or deflection. With the effect of joints appearing to be minimal, the analysis moved to a non-joint model evaluation.

The non-joint model chosen was WinJULEA. This program offers a simpler model, with easier input requirements, and quicker computation times. In order to perform some verification of this model and its output, the predicted deflections of WinJULEA were compared with those of ISLAB2000. The deflection predictions differed, as expected, but the trends were similar. In general, both models compared favorably. The final step was to determine how accurately the WinJULEA was predicting the behavior of the full-scale test section.

This was performed using selected pressure cell data recorded during full-scale test section traffic. There were some limitations in the data set; however, the results were encouraging. In general, the model is capable of predicting the initial stress response of the test section. The model showed similar trends to the recorded pressure data. As the distance to the boundary conditions increased, the model became quite stable, and in

some instances, the model's predicted stress only differed from the recorded data by a few pounds of pressure per square inch.

Clearly, more data, especially with differing soil types and perhaps even differed aircraft loads, would allow a more inclusive comparison. The modeling analysis here has clearly shown that simplified models, such as WinJULEA, offer some usefulness for initial evaluation of airfield matting systems. The model will allow the user to quickly analyze a matting system and compare its initial response to loading with that of other mats with similar characteristics and parameters. Even in the absence of similar response data, the model still closely predicts initial response, and this could suggest the potential performance of the mat when applied to varying base soil strengths. In either scenario, the model offers the researcher a very inexpensive, "first-cut" evaluation of a matting system without the costs of building full-scale test sections and performing traffic.

In closing, it should be reiterated that the specific models evaluated here were focused on the initial response of a matting system under a load. In the forms examined, these models will not allow for the prediction of long-term performance. This prediction would require the accumulation of deformation (elastic and plastic), and should include functions to account for and accumulate matting system (mats, joints, pins, connections, etc.) damage. Such models that include these accumulation and damage functions do exist, and some utilize the same mechanics as WinJULEA and ISLAB2000. However, their use is quite complex and require highly experienced modeling expertise to utilize.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

This research focused on the use of commercial airfield matting systems for contingency airfield taxiways and parking aprons where the expected primary traffic is the C-17 aircraft. The focus was testing of matting systems on medium-strength (California Bearing Ratio (CBR) of 8 to 10) soils and low-strength (CBR = 5 to 6) soils. The following are some conclusions from the research conducted.

Full-Scale Test Section

The DURA-BASE® matting system offers the best option for contingency matting on both medium- and low-strength soils. It allows minimal deformation (rut) to occur and is capable of withstanding the traffic loads of the C-17 with minimal mat damage, even after large pass levels. However, this mat is large and heavy and requires material handling equipment (MHE) such as a forklift to move and place the mats. The logistics of this matting system will probably make it a poor choice for contingency operations. When applied to a medium-strength soil, this mat sustained 1,000 passes with only 19 mm (0.75 in.) of rut. Over the low-strength soil, it offered 800 passes prior to rut failure 76.2 mm (3 in.). The DURA-BASE® mat is acceptable on any soil with a CBR of 6 or greater when C-17 traffic is expected.

ACE-Mat™ offers a good option for contingency matting. It offers an acceptable matting system at a much lower weight than the DURA-BASE®. ACE-Mat™ is light enough to be easily carried by two men. It is quite durable and shows minimal damage, even when subjected to large deflections over very weak soils. When used over a medium-strength soil, ACE-Mat™ sustained approximately 550 passes prior to the formation of a 76.2-mm (3-in.) rut (permanent deformation). When applied to a low-strength soil, the mat performed poorly, offering only one pass prior to rut failure. Clearly, ACE-Mat™ is only to be used on medium-strength or stronger soils when C-17 traffic is to be applied.

BRAVO® mat was only tested on the medium-strength soil. It failed mechanically after only 60 passes. The failures included pin breakage, corner breaks, crushing, and mat surface delamination (separation of the mat top surface layer from the internal frame structure). The BRAVO® mat is not recommended for use under the C-17 under any circumstances.

Of the three matting systems tested, all failed by rut depth criteria except for the BRAVO® mat, which failed mechanically.

Matting System Modeling

ISLAB2000 modeling efforts showed that for the matting systems analyzed here, neither the joint type nor the position of the gear, relative to the joints, appears to affect deflection or tensile stress conditions of the mats to any significant degree. In conclusion, the joints of airfield matting systems, specifically those with the overlapping/

underlapping joint type, have little effect on the response of the mat to applied load. For modeling of initial response to applied loads, these joints may be disregarded.

Because joints in the matting systems appear to make little difference in model response, the use of a simpler, layered elastic type model is acceptable. The layered elastic analysis model, WinJULEA, offers an easier method of modeling that requires simple inputs, produces results in very short time, and is easier to manipulate than the ISLAB2000 system, which is a 2-dimensional finite element analysis program. WinJULEA and ISLAB2000 are most easily compared using deflection as ISLAB2000 does not calculate stresses below the mat itself. WinJULEA compared very well to ISLAB2000 and produces similar deflection predictions.

WinJULEA compared very well to full-scale test section data. When the model's predictions of stress at various depths below the matting system were compared to the stresses recorded by pressure cells at the same depths, the results showed similar trends and gave the same range of values. The further the distance from the boundary conditions, in this case the matting itself, the more accurate the model's predictions of pressure became. In some cases, the model's predictions only differed by a few pounds of pressure from the test section recorded values.

WinJULEA offers a simple method of performing inexpensive "first cut" evaluations of a matting system. By modeling new matting systems with this program, an indication of initial response to loading through a measure of deflection and various stresses can be determined. By comparing these numbers to historical empirical data collected from full-scale test sections, some indication of long-term performance of a

matting system can be determined. This effort could mean saving the researcher many dollars on building a test section that may, in some instances, not be required.

Recommendations for Further Research

The work presented in this effort was limited in the amount of data that was present and could be used. With instrumentation data available only on the silty-sand full-scale test section (CBR = 8 to 10), this provided limited data and therefore limited analysis in this instance. Future efforts should focus on the use of pressure cells at different depths in test sections built from other soils such as clays, gravels, pure silts, pure sands, etc. In addition, several different traffic loads and configurations (such as the C-130 transport aircraft and the F-15 fighter aircraft) could be applied to these different test sections. These additional efforts could offer more field data to be used in further validation of the WinJULEA model and would provide a larger database for predicting long-term performance.

In this research, the deflection measured plastic deformation (rut), which was one of the criteria required by the research program. Future efforts should find effective, safe means of measuring matting system deflections with the load cart in place (elastic and plastic deformation). This full deflection is predicted by the models, such as WinJULEA, as an initial response of the matting and soil foundation systems. Without these total deflection measurements, the model can only be compared to such data as the test section pressure cells. This was one of the limiting factors of the modeling analysis in this project.

Finally, more effort should be devoted to developing and applying three-dimensional models and advanced material models to airfield matting studies. Use of more complex models will result in better agreement between measured and predicted responses of matting systems under aircraft wheel loads. In addition, the advanced models can offer an accurate means of accumulating deformation and mechanical failures within the mats during long-term performance, both of which play key roles in determining how much traffic a matting system can endure prior to failure.

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14. ABSTRACT

The U.S. military requires the ability to rapidly deploy troops, equipment, and materials anywhere in the world. Recent operations have brought attention to the need to utilize austere, unsurfaced, and sometimes sub-standard airfields within a theater of interest. These airfields may require additional taxiways and aprons. One option for the rapid construction of such is airfield matting systems. The focus of the work for this thesis was commercially available airfield matting systems to support large military transport aircraft, such as the C-17. Several test sections with differing strength soils were built with chosen mats tested in an elimination method, using a load cart that simulates contingency loading of one main gear of the C-17. Matting systems were evaluated based on logistical and assembly requirements, and deformation and damage sustained during traffic. A modeling effort was performed to investigate the potential of a simple model to predict the response of these matting systems under full-scale testing.

15. SUBJECT TERMS

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	C-17	Test sections

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